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PREDICTING HUMAN PERFORMANCE IN SPACE ENVIRONMENTS

by Warren H. Teichner and Diane Olson

Prepared by
HARVARD UNIVERSITY
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Preface

The ability of the astronaut to carry out the tasks required of him may be threatened by the environmental variations to which he is exposed. It is important, therefore, that limits of exposure be established and that the design of the astronaut's environment, the nature of the tasks, and the scheduling of effort be given rigorous, technical consideration. Unfortunately, the scientific data available concerning the effects of environmental factors on human performance are very sketchy and unsystematic both with regard to the environments and levels of environments that have been studied and with regard to the nature of the tasks that were used. Thus, while it is possible to summarize what has been done, it is more difficult to apply what has been done to the setting of exposure limits or to the prediction of performance in different environments for different periods of time. Doing this is also handicapped by the lack of a classification system with which to categorize tasks and by the lack of a systematic or theoretical approach which permits the deduction of environmental effects for conditions which have not received sufficient experimental study.

This report is an attempt to systematize the description of tasks and performance in a manner applicable both to the analysis of the environmental literature and to the operational situation. The nature of the approach was:

1. To develop a general classification scheme for the description of tasks.

2. To develop postulates from the basic literature of psychology so as to formulate a quantitative model of wide scope representing fundamental behavioral processes assumed to underlie performance at the tasks. Where

postulates were not implied by the literature, but appeared necessary, or where the literature did not permit quantitative formulation, assumptions were provided.

3. To develop relationships between environmental conditions and major physiological effects known or thought to result from them.

4. To postulate relationships between selected ones of the underlying behavioral processes and the physiological effects and then to use these relationships along with the performance model to predict the effects of the environment on performance.

5. To develop a general criterion for determining the environmental conditions which should be considered limiting.

We must emphasize that because of time limitations in this attempt we have been concerned less with the validity of any particular postulate than we have with the need for having such a postulate. As a result, we have made minimum use of the basic psychological and physiological literature; instead, we have relied on studies already known to us and easily accessible as a basis for our detailed assumptions. We know that given more time we can improve on them enormously. On the other hand, we have not skimped on the environmental-performance and environmental-physiological literature. Where that literature has provided data of relevance we have used it as the data to be predicted. The test of our approach lies in an evaluation of whether improvement of the performance model will lead to improvement of the predictions. At this state of development we ask only that our predictions resemble the actual data with a fairly large error.

Actually, as it will be seen, our predictions often come close to what data are available. This lends credence to the procedure and suggests that it be improved and extended. Finally, we should note that the possible variations of task details are too large to be handled in one attempt. We have, therefore, restricted ourselves to the development of a model for general use, but with postulates for only some of the variations possible within any one task category. Similarly, in selecting environments to study, we have put our major efforts into those which are most easily amenable to our approach as these provide the quickest way to provide tests of our predictions. Other environments are discussed, but in some cases more programmatically than otherwise.

In summary, we do not hold with undying fervor to our particular set of assumptions. We know that these will be altered in further study. On the other hand, crude as the approach may be, we do feel that it provides a systematic, quantitative approach to questions about the effects of environmental conditions on astronaut performance and that even in its present state of development it: (1) Points up the kinds of information which are needed, but are not available for this purpose, and (2) Provides an explicit system of rendering an estimate. This is to be contrasted with the "educated guess" which is usually based upon many fewer and less explicit considerations than we are offering.

This whole report is in several parts. The first presents the general theory and methods of its application. Herein are contained the assumptions developed about task classification and about performance independent of stress.

Also developed is the use of response blocking as an intrinsic performance criterion. In some cases, we have not yet been able to resolve our thinking about the best assumptions to be made at this time. Those cases are denoted explicitly and temporary steps taken to circumvent the problems that they raise. In all cases, as noted above, the specific assumptions are expected to be altered during a subsequent revision of the model.

Following the first part will be three others each of which is an application of the basic concepts to specific environmental areas. In each case, the same basic assumptions about performance are used, but somewhat different physiological relationships are employed. The reasons for each selection and the physiological assumptions made are discussed in the separate parts in which they are relevant.

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Predicting Human Performance in Space Environments

I. Theory and Method

I. Statement of the Problem

Any attempt to provide a systematic framework which can be used for predicting the effects of the physical environment on human performance has to contend with three major obstacles:

1. There are few experimental studies available which can be used to provide a basis for a systematic approach.

2. There is available, as yet, no general behavioral or psychophysiological theory which subsumes the effects of environment on human performance. There are, however, psychophysiological and behavioral concepts and models which might be integrated, at least tentatively, to establish a first set of working hypotheses.

3. Although a variety of approaches are available for the analysis of human performance, none seem to have gréat relevance as aids in analyzing the experimental literature from which environment-performance data must be obtained. Human engineering task analyses suffer from: (a) an overburdening detail which may be useful for design analysis purposes, but which lend little utility in classifying the rather skimpily described tasks used in the literature, and (b) a lack of correspondence to theoretical concepts. Again, some part of this is due to the detailed nature of the descriptive systems used. Such systems tend to be descriptive in an anatomical sense when what is needed are more functionally oriented task descriptions.

Opposed to task analyses in their approach are functionally oriented human performance models. For the most part these have taken the lead from control systems engineering (e.g. Ely, 1963; Fogel, 1963; Gagné, 1962; Pew, 1965). These models are suggestive and we shall draw upon them to develop an approach to the analysis of tasks.

Available control system models have been "black box" in their approach to intervening physiological mechanisms. This approach does not seem to be practical when considering environmental effects, if for no other reason than that the most frequent environmental data that have been obtained have been of physiological effects rather than performance. To take maximum advantage of the available information, it is necessary to develop performance-physiological relationships and then to use these to predict the effects of the environment on performance for conditions where physiological, but not performance data, are available.

In summary, it is our purpose to develop an admittedly tentative theoretical framework to represent the dependence of human performance upon the physiological processes which intervene between the environmental input to the human and measures of his performance. We shall use available concepts and theories as best we can, but we shall not feel bound by them. Such an approach has at least heuristic value; it serves to provide a working logic, though imperfect, to be improved upon, or replaced as evidence is gathered. It may lead to a more rigorous framework, albeit a different one. It should also serve as a basis for determining the major requirements of systematic research both to improve the concepts as such and to increase their power in predicting environmental effects. In fact, the practical criterion of goodness of the approach must be the degree to which it provides methods for predicting exposure effects and setting exposure limits.

A. The Analysis of Performance

Performance can be measured only by providing an individual with a task and observing such quantities as errors and the speed with which a criterion level of accomplishment occurs. It is important to distinguish between behavior as human reaction independent of the non-human aspects of tasks and performance, i.e., the behavior of a man-machine system. By the simple motion of his finger (behavior) an individual may throw a toggle switch (performance), press a button, communicate with another individual, shoot a gun, lift a cup, or give a command. To some degree human behavior can be measured independent of its effects. For example, the speed and extent of finger motion can be determined when the individual is instructed to behave by moving his finger as far and as fast as possible. It is true that in a man-machine task, the speed of finger motion depends upon both behavioral characteristics and the nature of the hardware with which the human response interacts. It is also true that the behavioral processes upon which the performance depends are conditioned by the environment within which they occur.

B. The Evaluation of Performance

Equally important is the recognition that the criterion of accomplishment, whether of the human or of the man-machine complex, is external to the task. That is, how much error can be tolerated, or with what speed responses must occur to be acceptable, varies from one mission requirement to another. A human reaction time might be acceptable for one task, but too slow for another. This is in contrast to human physiological functions for which, at least in principle, it can be said that some levels of response are unacceptable regardless of the situation because they threaten the physiological integrity of the individual. Tissue damage and unconsciousness are criteria for which there have been no behavioral equivalents. As a result, unless there is available a specific, mission-derived, external performance criterion, it has not yet been possible to analyze environmental effects into those which produce too large a decrement in performance and those which do not. We shall propose response blocking as a criterion which does reflect changes in the integrity of the behavioral processes on which performance depends. At the same time we shall attempt to provide the entire environment-performance relationship and thus to permit the individual user to apply unique system criteria.

II. Task Definition

Figure 1-a considers both the man and the machine as components of a system. In terms of this conventional diagram, we can think of information or data as being transmitted between components and as being operated upon or processed within components. We shall call any operation on information _within_ a component a _process_ and we shall define a _task_ as a transfer of information _between_ components. What is to be called a process and what is to be called a task depends upon the level of system analysis being employed. When Figure 1-a is analyzed into its subsystems, as in Figure 1-b, what was a process at the more general descriptive level may be seen to have become a task. That is,

there are now transfers of information between components which did not exist in Figure 1-a. Clearly, a process is carried out by subtasks and as the level of analysis becomes more detailed, successive processes break down into tasks.

Regardless of the level of analysis, the information transfer is always in the direction of machine-man-machine-machine. To analyze the effect of environments, or any other independent variable, it is convenient to deal with the transfer of information between each two successive components separately, i.e., in terms of the four major tasks, machine-man, man-man, man-machine, and machine-machine. The last of these falls outside of the scope of this paper.

A. Task Classification

Although what is to be called a task is dependent upon the level of description of the system, a separate task taxonomy is not needed for each level. Nor is a different set of task-descriptive terms required for each of the four directions of information transfer. As far as we can determine, regardless of the level of analysis or of the components involved, all four task categories act in only four different ways functionally to effect information transfers. We have called these four task activities searching, coding, switching, and tracking and by these terms we mean the following:

Searching: The exposure of a sensor to positionally different signal sources or to one source at different times. Searching is receptor orienting or signal seeking. It may be simple orienting as when the ears are positioned to enhance reception of a novel stimulus, or successive orienting also called scanning. Examples are monitoring, reconnaisance, target seeking.

The descriptive measure that will be employed is the probability of detection.

Switching: A discrete action which changes the state of the next component in a system. Examples are turning anything on or off, go or no-go, or, in general, making a discrete, selective action involving categorical choices. In a system sense, switching should be described as the time between the initiation of the signal and the completion of the switching response. However, this time will depend critically on the characteristics of the switch that is used. Thus, movement time will be longer the longer the required switch movement, the greater the required torque, etc. Since these factors cannot be anticipated, they must be estimated from specific analysis of the system of interest. Aside from these factors, switching responses vary in the time from the initiation of the signal to the initiation of the response, that is, in reaction time. Therefore, the reaction time or latency is the descriptive measure that will be used to describe switching.

Coding: The naming or identifying of a detected signal. Simple coding involves the attachment of a name to characteristics of a stimulus such as color, pitch, direction of movement, position, etc. Group coding refers to the grouping of stimulus characteristics into a single classification such as silverware for knives, spoons, and forks, or "John" for a person, or "attack" for a battle procedure, etc. Successive coding implies a syntax or set of rules which is used to relate or transform names or codes. Examples are translating language and computing. The descriptive measure to be used is the percent of correctly coded responses or equivalent such as the percent of error.

Tracking: Alignment of a response with a changing input. Tracking may be pursuit or compensatory as conventionally used. Examples of tracking are steering, aiming, walking, tuning. The measure to be used will be the percentage decrement in time on target. The use of a relative measure is dictated by the fact, as with switching, that actual time on target will depend on target width, etc. and, therefore, must be determined uniquely.

Complex Tasks: Many tasks can be thought of as combinations of the above carried out either simultaneously or in succession. For example, problem solving may be thought of as successive searching plus coding, plus switching; reading may be thought of as successive coding plus tracking; handwriting may be thought of as tracking plus successive coding.

Later we shall be concerned with the processes on which these tasks depend. In making postulates about them, we shall assume that complex tasks depend upon the same processes as do their simple task components. This, clearly oversimplified assumption of additivity, will be necessary in order to make any beginning toward dealing with complex tasks.

Tasks may be described in terms of the direction of information flow, or in terms of the functional activity describing the manner in which the information is transferred. These functional activities or tasks may be characteristic of any direction of information transfer. A man-machine task, for example, implies a transfer from man to machine which can be accomplished by means of tracking, switching, coding, searching, or a combination of these. This description will not be confusing if it is kept in mind that the task is a function carried out by the man-machine system rather than by the man or by the machine. It must also be remembered that our analysis in terms of two-component systems is a convenience. Due to this type of designation, it will appear that tracking and switching tend to be associated with man-machine or man-output activities and searching with machine-man or man-input activities. Coding, on the other hand, is easy to associate with either type or activity. Man-man tasks can be thought of easily in conjunction with all four functional tasks, although we shall see later that certain, intervening processes depend upon specialized task relationships.

B. Task Parameters

Tasks are characterized by the complexity of their input-output relationships, by the rate of input and of output, and by duration. In considering the last of these, it will be important to make a distinction between the duration of activity at a task and the duration of exposure to an environmental condition. They may or may not be the same. For example, an individual may be exposed to a high temperature for some period of time before he starts a task. Or the environment may change while he is performing the task. As will be seen later, the effect of duration of exposure will be expressed by the physiological state associated with a given environment for a given period of time. That is, the same physiological state might result from an intense environment for a short time as from a less intense environment for a longer time. The duration of the task, on the other hand, affects performance even when there is no environmental stressor. It will be necessary, therefore, to account for task duration in the basic human performance model.

Signal inputs and response outputs have rates. Although the input and output rates may differ in a task, and although each can be expected to make its own contribution to a performance decrement, we shall consider only the input parameter and assume that output rates are either perfectly correlated with inputs, or that when the rates differ, the input rate will be of much greater concern. This simplifying assumption should be reevaluated in further study.

Complexity is an elusive concept. We view it in terms of the amount of information in the signal (signal complexity) or the amount of information in the response (response complexity). Whether the experimental literature is sufficiently precise to permit description in these terms is problematical. For the present, therefore, we are defining complexity simply in terms of the number of different possible signals involved in the task and in terms of the proportion of possible signals displayed at one time. As with rate, we shall deal only with the input side.

The input signal will be classified in terms of the smallest signal unit used to elicit a response. For example, if the reported experimental input consists of two complex, but coded signals, then it will be classified as a two-signal input regardless of other details. Consider Morse code; a dit-dah-dit is a single letter of the alphabet and if the Morse-coded letter were the signal for a response, then dit-dah-dit would be treated as one signal. On the other hand, if dit and dah were each used to evoke different responses, then dit-dah-dit would be a two-signal input, that is, it would have two uniquely different signals. Notice that the repetition of dit in this case affects the rate of signalling rather than the number of different kinds of signal. This could be carried farther by noting that the signal might be a word instead of a letter.

A single response is considered to be a discrete event as opposed to a sequence of response events. Examples of single responses are the throwing of a toggle switch or any other single control action or the verbal report of the presence of an input. In general, a single response is something which provides a single coded input to something else and which itself is the only likely response event given the input. In contrast, multiple responses may be of three different kinds:

a. A single discrete event (as above), but one that has been selected from two or more possible responses that can be made given the input.

b. A number of different responses occurring simultaneously, for example, the simultaneous throwing of a toggle switch, operation of a foot control, and a verbal command or report.

c. A temporal sequence of responses such as in tracking, speaking or equipment checking.

The complexity of a task involves factors other than those present on a single trial. Given a task with any one of the four input-output complexity levels described above, the complexity of the task will increase with an increase in the number of different possible signals in the task as a whole. That is, task complexity will not only depend on the number of different stimuli presented simultaneously, but also on the number of different signals which may be expected during the total task performance. This aspect of complexity will not be considered at this time. A further discussion of complexity classification will be presented in Section IV.

III. Intervening Central Nervous System (CNS) Processes

Referring back to Figure 1-b, it is generally understood that what we have called "human information processes" are processes carried on within the CNS. If this particular component of Figure 1-b were analyzed into its components, one would expect to use terms like coding, computation, memory, etc. to represent the component activities. What these components should be has been discussed by a great many writers. Our decisions in this regard are based on a compromise between a desire for the fewest possible concepts about underlying processes and current research in neuropsychology concerning memory and other behavioral functions of the brain. The particular postulates and hypotheses that we shall use are based upon, but extend those of Teichner (1968). More detail and support for specific postulates may be found there.

Figure 2 presents a block diagram of central nervous system (CNS) functions which we are assuming to interact importantly in determining higher order task performance. The figure has three main divisions. On the left are the data-getting, machine-man tasks which involve sensory and receptor-orienting activities. These include sensory phenomena which are signals from both the internal biological system (man-man tasks) and from the external world (machine-man tasks). The internal world represents stimuli or afferent impulses which result from responding and from the state of physiological regulatory systems, e.g. the cardiovascular system, thermoregulatory system, digestive system, etc.

Search activities, shown on the left of Figure 2, lead to the acquisition of sensory data about the external and internal worlds. These data are transferred internally to the short-term memory (STM) where they are stored. If they are not selected from this storage by the attentional mechanism, the memory inputs dissipate as a function of time. If they are selected, it is by matching with an attentional filter whose characteristics are pre-set by long-term memory. This concept of attention, that is as a filter of varying bandwidth, was developed by Broadbent (1958) and since modified in a variety of ways and used by most writers concerned with the problem (cf Wachtel's review, 1967).

The attentional mechanism is coded by long-term memory so as to maximize the acceptance of desired signals and minimize the acceptance of irrelevant inputs and other noise. The greater the diversity among task-relevant signals, the wider the filter or bandwidth or region of signal acceptance. The wider the bandwidth, the greater the probability of acceptance of irrelevant signals. Although the concept is referred to the CNS, at the behavioral level its effect might be studied in terms of the amount of information transmitted in a single eye fixation.

The result of attentional processing is an acceptance or rejection of input data. Depending upon the criteria of acceptance, for example whether the signal has a desired target attribute, the information transfer from attention to searching will lead to a change in the searching direction or pattern. In the case of visual searching this would be exhibited as an altered pattern or direction of eye fixations. Thus, as Wachtel (1967) has concluded, attention.both filters signals and directs search.

A. Relationships Among Activation, Physiological Regulatory Processes and Attention

Also shown in Figure 2 is an activation process. Activation represents the various excitatory and inhibitory processes which are associated, at least, with functions of the reticular and limbic systems (Routtenberg, 1968). The results are both a widespread and a specific excitation and inhibition of other CNS areas. These include the arousal and de-arousal of the attentional mechanisms and, via effects on other CNS control centers, of the activities of the internal world.

The activation and attentional processes are crucial to this formulation in the same way that they are crucial to all modern approaches in physiological psychology. Although there is general agreement about the importance of these mechanisms, there is less agreement about the specific assumptions which should be made to relate the two. Basic to our thinking is the assumption that activation of the attentional mechanism produces two kinds of effect; one effect, already noted, is concerned with the region or bandwidth of signal acceptance, the other with the scanning rate of the sensory receptor. It is assumed that an increase in activation leads to a narrowing of the bandwidth for signal acceptance; thus, the probability of processing irrelevant stimuli to an accept-reject decision decreases. Secondly, we assume that as activation increases, and bandwidth narrows, the rate of attentional data-processing increases causing an increase in the receptor scanning rate.

The activities of the internal world are tuned by various CNS control centers. Additional control is provided by overriding mechanisms which are, presumably, triggered by the activating mechanisms. The effect of overriding control is a reversal in the ongoing direction of compensatory physiological reactions. Instances of such reversals appear to be cold-induced vasodilatation, reversal of the flexor reflex with fatigue, and a variety of other servo-like, protective responses. In the behavioral system the interruption of response in a high speed task, called Response blocking might be thought of as a reversal-dependent phenomenon. Reversals might also account for suddenly appearing erratic patterns of eye movements during search of a homogeneous visual field, and sudden erratic motor responses when complex tasks having highly varied inputs are carried out at high speed for relatively long times. All of these are related to the memory-attention data processing system described above.

We shall assume that reversals are produced when a ratio of afferent input rate to re-afferent output rate of any bodily subsystem reaches a critical value. When this occurs, the activating mechanisms are triggered and, via consequent facilitative and inhibitory effects, the ratio is reduced to a lower level at which point the activation effects are decreased or stopped. The result is a return of the output activity to its original direction. It is possible for the ratio to increase then, for a second reversal to occur, etc. and this will be seen as an intermittent reversing of the output reaction.

In the case of bodily reactions, all physiological reactions are assumed to have sensory consequences (i.e. re-afferents), at least in the sense that they provide inputs to the activating mechanism and can be detected by the individual. These sensory inputs are assumed to increase the activation level, but without producing reversals until the ratio of sensory input rate to the rate of change of the re-afferents is critical. According to this view, reversals are not produced by high activation levels; they may occur at low levels as long as the threshold ratio is reached. This is assumed to be true of all of the subsystem relationships shown in Figure 2 as well. Thus, if the rate of recoding is critically greater than the rate of oral speech production, pauses and or stuttering might be expected.

The requirement that the numerator of the reversal ratio be an afferent rate has interesting implications for sensory adaptation. That is, if the receptor is adapted, the effective rate of input signals is reduced. In this case it would be possible for an individual to expose himself overly long to a damaging environment since he would feel no great pain. The ongoing direction of compensatory reactions to the environment would continue longer, perhaps now in a maladaptive way. When bodily reactions in emotion are in the same direction as those to the environment, the output activity will increase, keeping the compensatory reaction going in the same direction. That is, it would be predicted that emotional states will prolong the time to reach a reversal level.

As Figure 2 shows, all sensory inputs lead directly to the activating system. Some of these inputs originate from external energies; others are associated with physiological activities. The figure also shows that these signals are processed through the attentional mechanism to the activating process. In the attentional mechanism signals are compared against criteria derived from long-term memory. If the signal has properties of novelty (that is, there has been little or no previous experience with it), or if it is perceived as threatening either in a physiological or psychological sense, no interference of the direct sensory activation will be produced. On the other hand, if, as a result of previous experience, the stimulus has been coded as non-threatening and familiar, the direct sensory induced activation will be nullified. This assumption allows for the interaction of environmentally produced and emotionally produced physiological reactions. It also accounts for the phenomenon of habituation.

To extend the concept of a critical input/output ratio at which reversals occur to short-term memory and attention, it will be assumed that at some critical ratio of short-term memory storage rate to the rate of attentional processing, there will be a sudden reversal of the bandwidth. This will be elaborated below. With regard to the effect on scanning rate, which is a bandwidth dependent phenomenon, a reversal of scanning rate from very high to very low would be predicted at some critical ratio for a narrow bandwidth. Since the bandwidth will have become very broad, scanning will not only become slow, but its tuning control will have become lessened and, thus, the scanning pattern should become random at this point. This assumption does not imply that a reversal will occur only at very high activation levels, but rather at any time a threshold ratio is reached. This is also true of the bodily processes. Furthermore, it does not imply that the threshold ratio must necessarily be the same for all tasks, although that is a possible assumption. Regardless of the threshold ratio assumed, it can be predicted that the various physiological and behavioral activities will reach reversal at different times.

From the foregoing, it may be seen that we have postulated a link between environmentally-produced physiological phenomena and behavioral phenomena via the sensory effects of bodily reactions, an interaction between activating and tuning functions and the data-processing (STM/attention) ratio. From the nature of the postulate, there should be no additional activation derived from the awareness of a sensory input, unless it is classified as threatening or novel. Similarly, a psychologically threatening stimulus which has only a minor physiological regulatory correlate would be associated with very strong, activation-produced bodily responses (emotion). The postulated interdependencies between activation and attention, and between physiological and behavioral phenomena are the fundamental relationships from which we hope to derive the effects of environmental factors on human performance.

B. Rate Phenomena in Short-Term Memory and Attention

Although we have discussed the interrelationship between attention and short-term memory in terms of the width of the acceptance region, we have said little about the rate of processing of data through the comparison process nor of the storage rate in memory. We have assumed that the more complex the acceptance criterion, the wider the acceptance region. We shall also assume that the more complex the stimulus input, the slower will be the processing of data through mechanism. More generally, we shall assume that the attentional data-processing rate is inversely related to the width of the acceptance region. Similarly, we shall assume that the rate of extraction of information from short-term memory is in phase with the comparison process. Thus, both criterion changes from long-term memory, which narrow the bandwidth, and increases in activation result in an increase in the rate of data processing and of extraction.

Our view of the short-term memory process is classical. We assume that some kind of signal persistence follows input to memory, but that the duration of the persistence is a function of a signal decay process which begins immediately. The amount of data storage in memory will then depend upon the input rate and the decay rate. When the input rate exceeds the decay rate <u>and</u> the extraction rate, a storage is developed. It is helpful to describe this in information theoretic terms (e.g. bits per sec.) since both the volume rate (ratio of number of signals presented to number of signals in the source) and time rate appear to be important (Teichner, 1964). From the foregoing, the following predictions can be made:

1. When the input information rate is less than the rate of information extraction (i.e. STM to attention), losses in memory will be small and speed of attentional processing will be high.
2. When the input rate is greater than the extraction rate, there will be losses of signals to be processed due to decay. The greater this ratio, the greater the memory loss.
3. When the input rate is greater than <u>both</u> the extraction rate and the decay rate, a memory storage will build up. As described above, when the rate of storage is critically greater than the rate of attentional comparison, there will be a reversal in the attentional

processing. If the bandwidth were relatively narrow, as with a relatively simple task, the reversal will be to a wide bandwidth. This will be manifest behaviorally as a pause in a series of responses, a phenomenon which has been called response blocking (Bills, 1937; Broadbent, 1958; Sanders, 1963). The result of the reversal will be a loss of signal flow from the attentional to the activation center and a consequent increased activation since there will be no attentionally-produced inhibition of the direct sensory activation. This increased activation, in turn, will result in a narrowed bandwidth so that attentional data processing will be resumed at a higher rate. After a short period of time the storage rate will have decreased, activation will be reduced and the attentional bandwidth will return to its criterion setting.

These postulates allow for the prediction of a momentarily increased response speed following blocking which has been reported in the literature (cf Broadbent, 1958). A second observed phenomena which can be predicted is a lesser loss of response for long duration as opposed to short duration signals. Although response speed increases following a block, a response can not occur to a signal which has decayed in short-term memory. Since short-duration signals are more likely to decay during the time a block is occurring, there is a lesser loss of response to long-duration signals. Also consistent with the experimental findings, it would be expected that blocking is most likely to occur for complex, high speed inputs since attentional processing will then be slow relative to input. Blocking will also be expected to occur intermittently after some initial period of performance. Finally, it is worth noting that if the task was not learned to a high level of performance, a shifting of bandwidth criteria would be expected as the individual attempted to apply different criteria from long-term memory. This would slow up the attentional processing and result in an increased ratio of storage to extraction rate. Thus, the probability of blocking at a given input rate would be less for highly practiced tasks.

Response blocking is assumed to be associated with a shift from a narrow to a wide bandwidth. If the task is complex, the bandwidth will be relatively wide in order to accommodate a diversity of signals. Furthermore, the rate of attentional processing will be slow. Under these conditions, a relatively slow input rate may be sufficient to produce a critical STM/ Attention data-processing ratio. The subsequent reversal, however, will be to a narrow bandwidth. The effects to be noted as predictable from this are: (1) A loss of relevant signals being processed through attention and a consequent increase in errors, and (2) An increased speed of attentional processing and a resulting reduction in the data-processing ratio. Thus, the reversal from a wide to a narrow bandwidth leads to an increased response speed, but with an increased error.

Both kinds of reversal require an input rate and consequent STM storage rate that is greater than the attentional processing rate. The same assumptions have implications for situations in which the input rate is very slow as occurs in prolonged monitoring tasks. In these cases, even if the task is simple, and therefore, the bandwidth narrow at the beginning of the vigilance period, if the signal rate is very slow, the activation level will be reduced and as a result the bandwidth will become somewhat wider. As with a complex task, a wide bandwidth implies a greater probability of processing irrelevant signals and a wider scanning pattern. The wider scanning pattern may decrease the probability of reception of the signal when it occurs; the processing of irrelevant signals decreases the probability of selection of the signal as relevant when it has been received. Thus, very slow input rates as in vigilance situations may lead to a reduction in the probability of responding to a relevant signal and an increase in the probability of responding to an irrelevant signal.

We have made attention a critical process and via this process and its interaction with the activating process we can now relate the physiological effects of an environmental exposure to man-machine and machine-man tasks. It should be pointed out that we are assuming an individual who is well learned at the task to be performed. The learning is expressed in Figure 2 as a set of long-term memory banks and well-defined coding, computing and recoding processes. If the individual is not well practiced at the task, then coding and computational errors may be high, the speed of selection from long-term memory may be slow, and the rules used for processing the data may be incorrect.

The output of the coding and computational processes is expressed as behavior, i.e. movements including speech, walking, and manual actions. The environment may have direct effects on motor activity and on sense organ functioning. Examples are an increased tremor during vibrations and a decreased thermal sensitivity of the skin during cold exposures. Such direct effects will, of course, tend to degrade performance and they need to be given specific consideration. Nevertheless, it cannot be assumed that they will always degrade performance since it is sometimes possible for the human to alter the way he does things so as to achieve the same end result. When this happens, an altered attentional state, and so an altered single glimpse information transmission and/or altered scanning procedure should be observed. That is, the individual may find some way to compensate.

C. Physiological Regulatory States and Performance

It would be convenient if the effects of the physical environment were to produce physiological compensatory reactions which were specific to each environment and physiological compensatory reactions which were common to all environments. If that were so, the theory could be applied most easily to the common physiological effects and studied in terms of the levels of common reaction produced and the relation of these levels to activation. Furthermore, by means of common effects, predictions would be possible from one environment to another. In fact, there probably are physiological effects which are common to all environments, but our knowledge of them is very limited. Where we know of common effects, we shall use them to predict across environments. An example, may be found in hypoxia. That is, to the degree that hypoxia is a common effect of reduced atmospheric pressure, of reduced oxygen intake, of transverse acceleration, and of some atmospheric contaminants, relationships between hypoxic reactions and performance may be used as a rough predictor base for any of these conditions.

The first step in analyzing the effects on performance of any environment must be an analysis of the compensatory physiological responses induced by the environment and of the sensory phenomena which accompany them. In considering the latter, careful attention must be given to the state of the receptor with regard to its adaptation to the environmental energies. For example, as pointed out by Teichner, Arees, and Reilly (1963), the stimulus intensity of a noisy environment depends upon the state of adaptation of the auditory receptor. If the receptor is adapted to the sound, the stimulus is effectively less. In the same way, the present approach demands that the individual's experience with the environment be evaluated since the activating effect will change the more habituated he is, or the more previous successful experience he has had with it.

We assume all environments have activating effects, although some of these effects are indirect. That is, some environments may debilitate a CNS control center. Nevertheless, we assume that there will always be compensatory reactions and that their afferent consequences will be activating even when the result of the compensatory reaction is to reduce the effectiveness of the environment. Thus, it is emphasized that the physiological conditions resulting from environmental exposures are not as important as the compensatory, regulatory reactions and their afferent effects. For example, exposure to high temperatures may produce some alterations in the internal body temperature, but the body temperature is a controlled variable. Of greater interest are changes in metabolic rate, skin temperature and sweating, which are compensatory responses which control the body temperature. It is in terms of these activities that sensory inputs and activation levels must be defined.

Even though all environments do not have the same critical physiological effects when they produce increases in activation, they may have similar activation effects. Some of these effects might be changes in heart rate, respiration rate, oxygen consumption, arterial oxygen saturation, and blood flow. If this is true, then these are the variables to which performance should be related and with which CNS variables should be related.

IV. Applications and Further Assumptions

The foregoing analysis permits us to develop tentative or hypothesized relationships which can be used as a basis for analyzing the environmental literature. In the following sections, we shall indicate specifically how to use the relationships being developed. It must be remembered that what is being presented is intended as a tentative, predictive system rather than as a finished product.

A. Tolerance Limits

In general, performance is analyzable in terms of measures of response speed and of errors. Acceptable limits of these measures will depend on specific task and mission requirements; thus, we will present entire performance functions so that external criteria may be applied. Regardless of task-specific criteria, it is desirable to have performance tolerance limits which reflect a loss of the integrity of underlying processes and, therefore, which should not be normally exceeded. The present approach suggests response blocking as useful for this purpose; that is, those conditions which produce response blocking represent unacceptable performance conditions regardless of the actual average performance level.

A response block is defined as an interruption of response in a continuous task. Most writers have used a pause of twice the normal reaction time* as the criterion for the presence of a block in such a task. This criterion will be adopted here. Then those conditions which just produce blocking will be used to express limits for acceptable performance. Actually, an interruption of response in a continuous task does have implications for system performance since such an interruption may be expected to increase the probability of failure at the task. Considering that as the severity of the environmental effect increases, the number and duration of blocks increases, any environmental level which just produces blocking may be considered to be the threshold environmental level after which the probability of failure increases.

For very slow speed tasks, as in some monitoring situations, response blocking, as defined, does not occur. A failure to respond is predicted, however, as the result of attentional changes. Although the concept differs somewhat, we shall use a failure to respond within twice the normal reaction time for the slow speed task as if it were a block. This is especially useful since, as with blocks, failures to respond must affect the probability of task success.

B. Classification of Tasks

We have already discussed the merits of having a task taxonomy based on functional rather than purely descriptive characteristics of tasks. Although a given type of task may have many variations, both in terms of procedure and in terms of role in system requirements, within the present context

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*It is very important to understand that by RT we mean the time from the initiation of a signal to the initiation of a response. This is to be distinguished from the time required to make a control movement which will depend on the parameters of the control.

all tasks shall be classified in terms of the four categories defined earlier: searching, switching, coding or tracking. A summary of the task definitions, as well as the underlying processes assumed important in the performance of each task, is shown in Table 1.

Table 1 is only a guide. Particular instances may involve a process which we have not indicated or such emphasis may have been put on some of the indicated processes that the others have only minor importance. Individual judgment is required on this point. We emphasize that it is a matter of judgment; however, the judgment must be made in terms of the definitions provided. It will be observed in Table 1 that all tasks are assumed to depend importantly on attention. Thus, judgments about the relative importance of underlying processes should be about the other three processes. Attention is assumed to be critical to every task.

It may be noticed that the defining characteristics of the tasks are based upon the measurement of performance to be used, as well as upon underlying processes. Thus, searching is measured by probability of detection (PD), switching by reaction time (RT), coding by percent correct, and tracking by time on target. Searching may be thought of as the most basic form of information transfer. Although it may be considered separately as a task, searching is a component of all complex man-machine tasks. This is easily understood when we consider that before any transfer of information (or task) may occur from one component to the next within a system, the information must first be brought into the system. Thus, the definitions given for the basic tasks defined as switching, coding and tracking, all assume the input from a prior detection or search activity. The importance of these assumptions will become apparent as predictions for task performance are generated in the following sections.

Table 1 also provides some examples of more complex tasks which may be classified by analyzing the total activity of the operator sequentially into a series of primary component tasks. For example, the operator may search, then code, then switch. Where more than one task appears to be going on simultaneously, a judgment must be made concerning the importance of the component task. If it appears that a particular task in a combination or a sequence is not critical to the total activity, it should be ignored. On the other hand, if all components appear critical, the effects of the environment on each should be determined as if the components were independent. The effect of the environment on the total activity would then be estimated by estimating the combined effects on the components in a manner to be described.

C. Task Parameters: Complexity and Rate

Accurate predictions of performance on a given type of task require knowledge of specific task parameters discussed earlier. Thus, having defined a task within the present classification system, the task should be further classified on the basis of complexity and rate of signal inputs. Although an ideal task complexity classification would deal with both number of inputs and number of outputs, we shall assume for practical purposes that the number of inputs is a more critical concern. Specifically, it will be assumed that either number of outputs and inputs are equal or that the outputs represent such well learned sequences of events that the critical factors are on the input side. Thus, each task may be classified into a complexity level based first upon the total number of possible task signals. Within each such complexity level, the tasks should then be described in terms of the number of possible task signals presented simultaneously. Most tasks will have six or less different possible signals; however, we will extend our analysis to a maximum of ten signals. Under normal performance, conditions having more than ten possible signals may be treated as if they had only ten.

Our previous assumptions concerning rate of information processing imply that blocking will occur sooner in a given task if the signals are presented at a faster rate. Since processing time is also dependent on signal complexity, an ideal input rate classification would describe tasks as being high-speed, moderate-speed, slow-speed, or very slow-speed depending on the relationship between signal presentation rate (seconds between signals) and the number of possible signals. High-speed tasks would then be defined as tasks at a given complexity level which have input rates just below those which cause blocking; the slower the proposed speed classification, the further the input rate from one which would cause blocking at that task complexity level. The advantage of the proposed speed classification system would be to give a quick estimate of how close various rate-complexity combinations are to a blocking threshold; this system would not specify the level of performance to be expected at a given combination.

The proposed rate classification system requires data concerning those combinations of task complexity and rate which lead to blocking. Unfortunately, although this information may be embedded in the data of existing studies, it is not readily available for use. Due to time limitations on the present project, we have decided to concern ourselves with predicting performance on tasks which we judge to have a moderate to high input rate.

D. Signal Detection and Search

Performance on any task depends importantly on the sensory reception of signals; for the present we shall only consider tasks involving visual signals. There are two components of stimulus detection which must be understood before we proceed to develop task predictions. One of these, stimulus detectability, is the probability that a stimulus which falls on a receptor will have enough energy to produce a sensory reaction. Relevant data are produced by psychophysical methods. Visual detectability will be affected by task conditions such as illumination, contrast, etc. Since our concern is with the biological effects of unusual environmental factors, we shall assume signals that are easily detectable under normal conditions. In any particular case of applied interest where this may not be true, the actual sensory detection probability can be established by standard methods and then incorporated into the sensory model to be described below. This model converts signals which are less detectable than P(D) = .98 to that value. Furthermore, to reduce the scope of effort to manageable size, we have confined our interests at this time to signals which are displayed briefly and presented a moderate to high rates.

The second type of detection is attentional, and is defined as the probability of a sensorially detected signal being accepted through the attentional filtering process. A signal which is rejected by the filter is considered lost to further processing and is functionally undetected. Any probability of detection which is not a pure sensory threshold measure is, therefore, considered to be dependent on both a sensory and attentional process. We shall use the term "signal detection" to denote this combined, or two component, process.

The simplest search task is one in which the individual is concerned with the detection of one signal arriving in a known position, but at an uncertain time. With relatively short time delays between signal presentations, i.e. a moderate-speed to high-speed task, the attentional factor plays a negligible role and the best measure of performance under normal conditions may be estimated by the sensory detectability of the signal. A task with this requirement is often carried out for a long time period, as in the usual vigilance experiment or in many operational monitoring situations. Under these conditions performance is expected to deteriorate in a manner to be discussed in a later section.

For most tasks the operator will generally know within some limited field, e.g. a display console, where the signal will occur, but will be uncertain about the exact position of the signal as well as the time of signal arrival. The case in which the operator knows the exact time of signal arrival but is uncertain of position is rare and will not be considered. In most tasks of interest the operator must deal with more than one possible signal; the task may involve search for one signal when many signals are possible, or the task may involve search for many signals presented simultaneously. In these tasks attention does play an important role in performance and must be accounted for.

V. Prediction of Normal Performance

A. Predictions of Normal Search and Switching Performance With Single Signal Presentations

We have defined the most basic search task as one for one signal occurring in a known position at an uncertain time. Under normal performance conditions, and at short task durations, the best estimate of task performance is based on the probability of signal detectability and is .98.

Search performance in a task with one possible signal having uncertainty in both time and exact position of arrival has been estimated as P(D) = .95 under normal conditions and at short task durations. This P(D) involves search-attentional relationships, thus, the estimate is lower than the sensory P(D).

We have hypothesized that an increase in stimulus complexity increases the attentional bandwidth, thus, decreasing the rate of signal processing, and increasing both the probability of signals dissipating in STM and the probability of errors in the filtering process. This hypothesis leads to the prediction that the probability of detection for any one signal will decrease as the number of different possible task signals (or information to be processed) increases. This expectation is presented in Figure 3 as a decreasing, positively accelerated function. The nature of this function has been assumed arbitrarily except for the constraint that the highest point be .95. A more exact hypothesis needs to be developed in future work.

The postulate that the rate of processing is a function of stimulus complexity also leads to the expectation that reaction time (RT) will increase (become longer) the greater the number of different possible signals available. Figure 4 presents the expected relationship between switching performance and stimulus number as an increasing, negatively accelerated curve. The function is similar to that obtained by Hick (1952). The data points plotted are those of Merkel (1885). The curve was fitted using .2 second to represent the normal visual RT to a single stimulus (Teichner, 1954). Figure 4 shows that there is a normal, or minimal, RT to be expected to a visually detectable signal with any given number of possible signals (N) presented in the task. Since blocking is measured as twice the normal RT for a given task condition, this provides the normative data required to define the blocking threshold at each value of N. For example, the figure indicates that the normal RT expected to one signal, given N = 4, is .45 second; a block would then be defined for this case as a RT equal to or greater than .90 second.

For tasks involving discrete presentations of one signal where N signals are possible, Figure 3 defines the maximal expected P(D) and Figure 4 defines the minimal expected RT. A combination of the values from these two figures provided the basis for the construction of Figure 5 which presents a series of curves relating RT and P(D) for one signal given various values of N. The curve for one possible signal (N = 1) was constructed by first plotting two points; the first point, (x, y), was plotted by reading x = P(D) from Figure 3 and y = RT from Figure 4. A second point was plotted assuming a P(D) = .2 to be related to a RT = 1 second. The curve connecting the two points for N = 1 was assumed to be a decreasing, negatively accelerated function with an asymptote at RT = .2. The curves for the remaining values of N were constructed by plotting the point (x, y) read from Figures 3 and 4, then interpolating the remaining curve values from the N = 1 curve. It may be noted that the interpolation was such that the limiting values of the N curves are not equal and the curves are not parallel. Whether or not the curves are assumed parallel leads to differing implications concerning interactions among stimulus complexity, P(D) and RT. For this reason, the shape of these functions should be an important concern of future research.

Figure 5 allows us to define unacceptable performance for a searching task as that probability of detection which is associated with a reaction time twice that of normal for the task. For example, in order to determine the unacceptable performance limit for a task involving search for one signal when two signals are possible (N = 2):

1) Read the normal RT for N = 2 from Figure 4 as RT = .32 second.
2) Multiply the normal RT by 2 to get the blocking level as RT = .64 second.
3) On Figure 5 construct a horizontal line from the ordinate value equivalent to the blocking RT (RT = .64) to the point of intersection with the N = 2 curve.
4) Read the abscissa P(D) value corresponding to the above point of intersection as the unacceptable search performance level; in this case P(D) = .423 is unacceptable.

The same process reversed indicates the RT corresponding to a given P(D) value at a certain level of stimulus complexity; the obtained RT is compared against the blocking RT, for that value of N as defined by Figure 4, to determine if the RT lies within the acceptable behavioral zone.

B. Predictions of Normal Searching and Switching Performance with Multiple Signal Presentations

Displays frequently contain more than one signal at a time. The The task may require that the operator detect and respond to each signal in a sequential manner, or with several responses simultaneously, or that he respond to some coded relationship among them (pattern). The latter case, as defined above, represents one signal even though it has a multiple of elements. The problem of multiple signal presentations, then, is that one which requires sequential or simultaneous responses. Of concern is the proportion of signals that will be detected and the speed of initiation of the first response, i. e. searching and switching.

Figure 6 presents the proportion of signals detected as a function of the number of different simultaneously presented signals. When the same data are expressed in terms of the absolute number of signals detected, it becomes apparent that four signals are the maximum number which can be detected for this condition (Teichner, Reilly, and Sadler, 1961). Although the absolute number detected remains constant with increasing N, the proportion of displayed signals detected decreases. It follows that the probability of detecting any number (n) in N displayed decreases and may be expressed as the proportion detected, i. e. n/N. Figure 6 then may be viewed as the probability of detection of n signals in a search task involving N simultaneously displayed signals.

There are no data readily available to use which relate RT to level of complexity for the multiple signal case. Furthermore, in comparing the one- and multiple-signal cases, it is difficult to select among several alternative possible assumptions about the speed of attentional processing. One of those equally attractive alternatives is that the speed of processing is the same, i. e. the filter is the same for the two cases as long as the total number of displayed and possible signals are equal. Since this seems to fit within the model with no empirical basis for deciding otherwise, this is the assumption that will be used.

On the other hand, the nature of searching directed by attention will differ depending on whether one or several signals are displayed. For a constant area of search, the probability of detecting any briefly exposed signal will be greater, the greater the density of signals in the area. This has been shown by Teichner, Reilly, and Sadler (1961) and partly accounts for the initially high probability and flat function of Figure 6. Furthermore, the minimal RT, that is the one associated with the greatest P(D) for a given N, should be the same as the RT associated with the same P(D) for the one-signal case. For example, if we are concerned with performance on a task involving 5 simultaneous signals we would:

1) Find the proportion of signals detected by reading P(D) from Figure 6 as P(D) = .8.
2) Using Figure 5, construct a vertical line from P(D) = .8 on the abscissa to the point of intersection with the N = 5 curve.
3) Read the ordinate RT corresponding to the above intersection point as RT = .511 second.

The RT obtained in the example represents the minimal RT or that response speed to be expected when the probability of response is maximal. However, the form of the relationship, RT = f(P(D)), is likely to be different from that shown in Figure 5, and therefore, a different model appears to be required. This is shown in Figure 7 which will be recognized as a family of curves somewhat different in construction, but similar in use to that of Figure 5. As with Figure 5, a response blocking threshold can be established by determining the appropriate RT from Figure 7 and doubling it.

The curve shown in Figure 6 is based upon a sensory probability of detection of .98 at least. If under normal conditions that probability has been lowered due to variations of the parameters of the stimulus, the appropriate sensory probability must be used to weight the curve. This new sensory probability is obtained by methods to be explained below (cf Figure 12). Figure 7 is then used as just explained to obtain RT correlated with the adjusted P(D) for a given value of N.

C. Probability of Detection and Time at Task

Up to this point we have been concerned with the effect of stimulus complexity factors in affecting attentional bandwidth, the search process, and, thus, P(D). Other task parameters will also affect the attentional component of the probability of detection; the most important is time at task. For the one-signal case, with increasing time spent at the task, the effects of continued responding and of restricted activity lead to deactivation. In terms of our previous hypothesis this would produce an increase in attentional bandwidth, an increased probability of processing irrelevant signals, and therefore, a decrease in P(D).

Figure 8, based on Teichner's (1962) data, presents changes in the P(D) for a visual signal as a function of duration of the monitoring period. The figure provides different curves for several initial detection probabilities ($P(D)_i$), the uppermost curve being for a signal initially easily detectable ($P(D)_i = 1.00$). Although the data are based on one signal presented in a known position, we will use these curves as the best available estimate of the relationship between time at a task and change in initial P(D) for any type of search task. Curves may easily be constructed for any initial P(D) value by interpolating from P(D) values on the graphed curves immediately above and below the P(D) value being considered. Since the curves are not parallel, the user is cautioned not to interpolate from the P(D) = 1 curve alone. For example, if the $P(D)_i = .90$, then the interpolations for the new curve would involve the 1.00 and .75 $P(D)_i$ curves on the graph. The equations involved for interpolations of any $P(D)_i$ value may be found in section VIII. RT values corresponding to the change in $P(D)_i$ may be obtained from Figure 5 or Figure 7 depending on whether the task involves single- or multiple signal presentations.

The vigilance research literature appears to suggest that the loss in the probability of response which occurs with prolonged monitoring occurs when the rate of signal presentation is slow, perhaps of the order of four signals per minute or less for the multiple signal case and then, perhaps, not at all for more than three signals. Since our predictions in this report will be limited to moderate and high presentation rates, the time factor will be important only to the case of one signal displayed at a time.

If the task involves a duration of time at searching, the curve must also be weighted by the attentional factor represented in Figure 7. Under conditions of environmental exposure both the sensory and attentional factors used must reflect their own susceptibilities to the environmental variable. How this is done will be illustrated in Part II.

D. Normal Coding Performance

In order to carry out a coding task, it is necessary first to have completed a search task. The error in the coding will depend upon the probability of detection. It will also be related to switching performance since that too depends upon the probability of detection. In fact, it is fairly well established that the greater the coding error, the longer the reaction time. Coding and switching differ in nature, however, as one is measured in terms of the error in responding while the other is measured as the time to initiate a response. It follows that the response blocking concept does not apply to the coding task. That is, a measure of response error cannot be applied to the absence of a response. To apply the blocking threshold as a limiting condition when the task is coding, it is necessary, therefore, to determine it in terms of the switching task which has the same signal and environmental characteristics.

Figure 9 relates coding performance to stimulus complexity, i.e., number of signal categories, with the duration of the signal as a parameter.

The data were taken from Teichner and Sadler (1962) and the curves were fitted by eye. The data conform to the theoretical expectation of a decrement in performance with increased stimulus complexity. It would also be expected that a longer stimulus would lead to a higher percent correct, since a longer duration both allows the operator more search time and allows him to recheck his initial evaluation of the signal's identity.

It may be noted that we have not provided a way to separate out the components of the coding and memory processes postulated to underlie performance on this task. Future development of the theory will probably find this to be desirable. Our decision to confound the two processes for the time being has certain implications for the treatment of environmental effects on this type of performance. This means that we shall not provide separate estimates of the environmental effects on these processes, nor the relative contribution of these effects to the predicted coding task performance. Instead we shall provide an assumption about the interaction of attentional changes due to the environment with the joint effect of these two processes.

E. Prediction of Tracking

Unlike any of the previous tasks, tracking can be measured only in terms of the performance of a man-machine system. The reason for this lies in the fact that there is a feedback loop from the system output which, at least in part, provides the sensory input to the individual, i.e. the human operator. In spite of this, tracking can also be thought of as a serial reaction time or sequential switching task since from the operator's point of view, the task consists of a series of discrete corrective actions.

Tracking systems vary in complexity according to control order and within the lowest order of control, complexity varies according to the number of axes or dimensions of movement or of position controlled. The externally derived sensory input for position controls appears to require the same visual functions as the previous three kinds of task. The higher order (velocity and acceleration) controls, however, call upon the additional ability to discriminate velocity. Furthermore all tracking controls must be assumed to involve a computational process. Velocity and acceleration-controlling would appear to involve relatively high speed, complex computations; the computation requirement is presumably greater for acceleration controls. Position controls would appear to require less by way of computation, but the requirement should vary according to the number of axes of movement possible in the control. Because the input varies continuously, the computation involved is one which provides the operator with an anticipation of target position. As a result, he is able to make corrections before the control and display are appreciably out of alignment. The corrective actions and their associated reaction times are, thus, anticipatory and short as compared to switching tasks.

The operator's actual performance level will, of course, depend upon a variety of factors such as: the target width or scoring area, the frequency of the forcing function and the time lags in the system. Since target width will vary from one actual system to another, we will deal with arbitrary units and express our performance predictions in terms of relative error. We will also assume a forcing function of a reasonably high frequency. Specifically, we shall assume target width and signal frequency conditions which, combined, allow no better than 70% time-on-target.

Control systems are characterized by three kinds of time lag each of which degrades system performance: (1) Display lag, (2) Transmission lag, (3) Control lag. Human reaction time is a transmission lag. However, the total transmission lag can be thought of as the human transmission lag plus the control lag of the system. Because the analysis is simpler when this is done, we shall not distinguish between the two. We shall also assume that the actual machine control lag is small and constant. If in any specific case, this is not so, the actual control lag should be added to the human transmission lag on the baseline of Fig. 10.

Figure 10 presents the assumed effects of the human time lag on tracking performance. The abscissa, or transmission lag, represents a minimal actual machine control lag plus the anticipatory reaction time. The left-hand ordinate presents a single scale for use (1) as arbitrary units in dealing with studies which have reported absolute tracking error and (2) for use as the per cent of time-off-target for those studies which have used this kind of measure. The right hand ordinate presents the percent increase in absolute error for the values of the left-hand scale using 30 as a referent.

The curves shown in the figure were hypothesized as follows. The 2-axis position control curve was based upon the findings of Garvey, Sweeney, and Birmingham (1958) which indicated only a small initial effect with increases in the control lag for lags up to at least .75 sec. We have assumed that this curve should begin to rise at 1.35 sec. The 1-axis and the 3-axis curves were drawn to represent different orders of complexity using the 2-axis curve as a comparison. The velocity and acceleration lines were based upon data presented by Senders and Frost (1964) modified for present use. It should be noted at this point that we are assuming that the relationships shown by these two curves combine velocity discrimination and all computing factors. Other than these, tracking performance, or the anticipatory reaction time on which it depends will be a function of sensory and attentional factors.

Specifically, since the actual signal in a tracking task is the error or difference between the target and control output positions (pursuit tracking) or between the target and a desired position (compensatory tracking), we have made the reasonable assumption that the human transmission lag (RT_T) depends upon the probability of detecting the difference $P(D_d)$. The specific relationship assumed is shown in Fig. 11 where it may be seen that an inverse proportionality has been hypothesized. Note in Figures 10 and 11 that in the noiseless condition, e.g. when $P(D_S) = 1.00$, $RT_T = .2$ and that performance is identical regardless of the kind of control system.

F. Motor Factors

All of our predictions of switching performance are expressed as reaction times, i. e., the time to <u>initiate</u> a response. We have made no attempt to deal with either movement time or response completion time since movement depends on such specific hardwared parameters as the distance through which the switch must move, required force application, etc. Similarly, we have expressed tracking as a relative effect, since the absolute time on target will depend upon target width, cursor width, etc. In both cases, to predict the actual performance requires combining these kinds of information, obtained from standard sources and from study of specific systems, to our estimates.

Along the same line, certain environments are known to have important effects on the mechanical aspects of the motor system. Vibrations and accelerations are particularly important in this regard. Within the present system, these motor factors can be considered as sources of proprioceptive feedback which supply inputs to data-handling processes and to the activation mechanism. As such, they represent increases in the data-processing ratio. To deal with them, however, data are needed relating response blocking to motor impediments, and these data have not yet been found.

VI. Prediction of Environmental Effects on Performance

A. Sensory and Environmental Effects

Up to this point, we have said nothing about the sensory processes except to point to their role in acquiring data. Clearly, if these processes are operating at reduced sensitivity, there will be a loss in signal detection which is not due to either attentional processing or search activities. It is also clear that if enough signals are missed for this reason, there is not much point to further analysis with regard to the accuracy of performance.

Most sensory data are expressed in terms of some kind of threshold measure; for example, one visual threshold is that brightness of a light source which is just detectable. In most cases, just detectable is conventionally defined as that stimulus intensity (or other stimulus characteristic) which can be detected half of the time; however, some investigators prefer to define threshold as the 75 percent detection level in order to account for chance factors. Unfortunately, this means that most available sensory data are not directly relevant to the estimation of task performance since most actual tasks use signals that are easily detectable. A proposed solution to this problem will be treated later in this section.

Before discussing the effects of the environment on signal detectability, we should consider what a sensory detection measure is and what factors determine the nature of its measurement. The problem may be treated in a number of ways depending on the nature of the underlying statistical properties assumed of the retinal detection process, i.e., whether quantal or continuous. In addition to the properties of retinal receptors which determine the probability of detection, there are three classes of visual factor which affect that probability:

1) Diffraction and diffusion of the properties of the stimulus will enhance detection due to a single target characteristic by energizing a large number of receptors in the retina. This is especially important in the case of small sources.

2) Retinal interactions and binocular interactions will increase detectability of a target characteristic.

3) A combination of probabilities which is a consequence of the fact that the threshold or any given level of detection is defined statistically.

Detection on the basis of combined probabilities may be better understood by the following example. Suppose a target which has the attributes of size and luminance and suppose that each attribute is present to a degree representative of its independent absolute threshold. For this example, assume that $p = .5$ for each; then assuming independence, the probability of detecting one or the other attribute, i. e., the probability of detecting the target by either size or by luminance is,

$$P(D) = P_1 + P_2 - P_1 P_2 = .5 + .5 - .25 = .75.$$

We can approach this question differently by noting that the probability of not seeing the target on the basis of a size cue will be $(1-P_1)$ and of not seeing it on the basis of a luminance cue will be $(1-P_2)$ and the probability of not detecting the target on either basis will be $(1-P_1)(1-P_2)$. Therefore, if the individual probabilities are independent, the probability of detecting a target on the basis of at least one of two cues is:

$$P(D_S) = 1 - (1-P_1)(1-P_2) \ . \ . \ . \ (1-P_n) \qquad (1)$$

for the above example,

$$P(D_S) = 1-(1-.5)\,(1-.5) = .75$$

It is very important to realize that the $P(D_S)$, or combined sensory detectability so obtained, is conservative, an underestimate, since it assumes neither of the first two listed classes of factors both of which would increase the individual probabilities. In spite of this it is clear that detection of a target is more likely than detection of any one of its attributes. Thus, the use of individual detection levels will lead to the expectation of a poorer visual performance than should actually occur. For example, assume a visual target having three attributes under conditions where each attribute would individually have a very low P(D): luminance = $P(D_l) = .1$; size, $P(D_a) = .1$; and color, $P(D_c) = .1$. Then, $P(D_S) = 1 - (1-.9)(1-.9)(1-.9) = .281$ which is to say that the target will be detected by at least one of these cues 28% of the time.

The concept of a combined sensory detection probability, $P(D_S)$, gives us a basis for predicting the sensory effects of the environment by using available threshold data. That is, if we know that an environmental level causes a given decrement in the threshold of visual acuity, and of the brightness and contrast thresholds, the $P(D_S)$ value gives us an estimate of the effect of these losses on the total target detectability.

The typical study of the sensory effects of the environment is one which determines the increase in stimulus energy required for the stimulus to reattain threshold detectability. In order to make the available experimental data useful, it is necessary to determine what the environmental effect would have been if the detection criterion had been at least 98 percent detection.

Traditionally, sensory thresholds have been expressed as the mean of a normally distributed variable. Figure 12 provides a number of such distributions shown in the customary ogival form. The center of the abscissa, denoted as zero, represents the mean of the distribution, i. e. the stimulus energy associated with the 50 per cent detection level. Variations from this point indicate the stimulus energies required for detection at higher and lower levels. Thus, for any one baseline scale in the figure, the difference between zero and any indicated value is the amount that must be added or subtracted from the mean to obtain a given detection level. Since the mean stimulus energy value related to 50% detectability is itself dependent upon a great many conditions, this value will vary from study to study, and no normal mean value can be expressed. However, since the ogive is based on z scores, the mean stimulus value of any study can be set equal to zero and that zero value can then be used as the reference 50% threshold. Furthermore, if an experimental threshold level other than 50% was used, the ordinate P(D) value representing that threshold will indicate the appropriate basline reference point to be used.

Figure 12 can also be used to predict the stimulus intensity level required to obtain any given level of detection relative to a normal or control value. For example, suppose that because of various conditions of adaptation of the eye, background brightness, etc., a visual target were detectable 75% of the time when its size was 3 min. of arc. By setting 3 min. of arc on the visual acuity scale at .75, and by reading in both directions from it, the probability of detection of the stimulus size variable can be determined. Generally, the control value will have been based on a .50 detection level.

If under particular environmental conditions, a value of the stimulus energy must be added to the normal mean to maintain a 50% threshold, subtraction of that stimulus energy value from zero on the appropriate Figure baseline will indicate what the reduced P(D) of the mean signal would have been. For example, if under some environmental condition a contrast must be increased by .28 to maintain a 50% threshold, then the ordinate value corresponding to -.28 indicates that the original 50% P(D) would have decreased to P(D) = .08. That is, there would have been a loss of (.50 - .08) = .42 in the probability of detection. If we assume that the amount of decrement in detection, due to a given environmental level, will remain constant regardless of the initial P(D), we can determine the environmental effect on a readily detectable signal (P(D) = .98) by subtracting the amount of decrement found in the usual threshold measure. Thus, if the original signal in the example above had been 98% detectable, the detectability under that environmental condition would have been P(D) = (.98 - .42) = .56.

The environmental effect on the detection of a single target attribute, such as contrast, may be used to estimate the effect on total target detectability by substituting the attribute P(D) values into the $P(D)_s$ formula.

B. Physiological and Environmental Effects

We stated earlier that the first decision required for analyzing environmental effects on performance must be the selection of an appropriate physiological response to use as a link between performance and the environment. We emphasize here that we are only interested in compensatory physiological changes which are characteristic of unusual environment; we shall not be concerned with changes due to normal environmental fluctuations.

Ideally, we would like basic relationships between our underlying processes and physiological changes. We could then use the physiological changes in response to the environment, as a means to predict the performance effects of that environment. Basic relationships between physiological and performance phenomena do not appear to be available. Furthermore, there are only a few environmental areas in which both have been studied concomitantly. Thus, both basic and environmental data are unavailable.

In the absence of data we could have postulated specific dependencies of performance on physiological states. Instead, we have approached the problem by seeking correlations between the physiological and behavioral effects of the environment. Where basic and important physiological changes in response to different environments have been found similar we have attempted to correlate the effects of the environments on performance via the common physiological change. For example, as will be seen in Part II, we have assumed that any environment which induces hypoxia will have common effects on performance. To determine what these effects are we have:

(1) Postulated relationships between behavioral processes and physiological measure of hypoxia.

(2) Determined the different effects of the environments on hypoxia.

(3) Used the postulated behavioral relationships to predict the environmental effects.

C. Estimating Attentional Changes

Bill's (1937) data indicate that both the frequency and duration of response blocks increase with decreases in arterial oxygen saturation. This important finding implies that blocking is a behavioral effect which is controlled by activity of the central nervous system and which, among others, is susceptible to conditions which lower cerebral oxygen tension. These conditions include such factors as: CO, altitude, transverse acceleration, or in general, any condition which lowers O_2 uptake, transport or perfusion. We have postulated that blocking reflects changes in the attentional mechanism. These changes represent reversal reactions rather than graduated alterations in the attentional filters such as would be reflected by changes in the characteristics of searching. Nevertheless, since the only relevant environmental data are of blocking effects, we shall use those data as a basis for estimating relative attentional changes. The rationale for this use of blocking is further supported by the common report of an increase in blocks as an emotional reaction to emergency conditions and to conflict in decision making situations. Where the environment affects the frequency of and the duration of the blocks, we shall use the blocking duration effect since it appears to provide a more conservative estimate.

Future work should be directed toward eliminating this expediency by a direct study of the effects of the environment on characteristics of search.

D. Construction of Performance Prediction Curves

(1) Searching

Normal search performance is measured by the probability of signal detection, P(D). P(D) is defined by the joint probability of both sensorially detecting a signal and attentionally processing it, i. e.

$$P(D) = P(D_S D_A) = P(D_S)P(D_A/D_S) \qquad (2)$$

where $P(D_S)$ is the sensory detectability obtained by Eq. 1 (see section VI-A), and the conditional, $P(D_A/D_S)$ is the probability of correct attentional processing. It may be noted that under normal task and environmental conditions $P(D_S)$ is so high (.98) that for prediction purposes it may be considered to equal unity. In this case, normal performance, or P(D) is equal to $P(D_A/D_S)$; i. e.

$$P(D) = P(D_A/D_S) = P(D_A).$$

Accordingly, for normal performance, when it can be assumed that $P(D_S)$ is essentially 1.00, P(D) can be used as the estimate of $P(D_A/D_S)$. Then, under environmental conditions, the value so obtained can be weighted by an attentional loss factor. We have selected the percent increase in response blocking (Δ%B) for this purpose. Therefore, once the environmental-blocking relationship has been obtained from the literature, the probability of signal detection, P(D), at a given environmental level may be obtained by:

$$P(D) = P(D_S)\left[P(D_A/D_S) - P(D_A/D_S)\,(\Delta\%B)\right] \qquad (3)$$

A plot of the P(D) values obtained for many environmental levels forms the prediction curve for the effect of this environment on the search task. An unacceptable performance limit for a given search task is defined as that P(D) value which is associated with twice the normal RT in a corresponding switching task (cf. Section V). This value is obtained from Fig. 5 for search involving single signal presentations, and from Fig. 7 for multiple signal tasks. Any environmental level which leads to this or a lower P(D) value than the limiting P(D) can then be considered as undesirable for performance of this task. That is, the environmental condition represents the threshold of increase in the duration of response blocking and as such represents the onset of an increasing probability of failure at the task, regardless of the absolute level of performance.

In the case of search for one possible signal presented in a known position attentional processing is assumed minimal, and $P(D_A)$ is considered equal to 1.00. Therefore, no blocking is predicted and all terms drop out of Eq. 3, except $P(D_S)$.

A task involving search for one signal given N possible task signals is assumed to depend importantly on attention and to evidence blocking at some environmental levels. In this case the normal $P(D_A)$ (and, therefore P(D)) has been assumed to be a function of signal complexity as shown in Fig. 3. The environmental performance effect for a given value of N is obtained as follows:

1) For the chosen value of N read P(D) from Fig. 3.
2) Substitute this P(D) for $P(D_A)$ in Eq. 3.
3) Enter appropriate $P(D_S)$ and (Δ %B) for a given environmental level and calculate the new P(D) value.

4) Repeat the process obtaining P(D) values for each considered environmental level.

5) Plot P(D) as a function of the environmental physiological measure.

6) Draw a horizontal line from the limiting P(D) value to define unacceptable performance.

The combined effects of environment and search duration, or time at task, may be obtained by considering the P(D) value at each environmental level as the initial probability of detection in Fig. 8. The new P(D) values at various time intervals are then obtained by interpolating from the given curves as described in Section V-D.

Search for Multiple Signals is measured in terms of the proportion of simultaneous (N) signals detected, and complexity is defined in terms of N. The method of predicting environmental effects is identical to that given above for search involving one signal given N, with the exception that the $P(D_A/D_S)$ value in Eq. 3 is estimated by the normal P(D) at a given value of N as expressed in Fig. 6.

(2) Switching

We have assumed that the relationships defined between P(D) and switching performance, RT, for a given task type remain constant independent of environmental conditions (cf. Sections V-A, V-B). The environmental effect on a switching task performance is obtained as follows:

1) Determine which type of searching task involves the same signal parameters as the switching task.

2) Obtain the P(D) values for that search task as described above.

3) Read the P(D) value obtained at a given environmental level into the baseline of the appropriate P(D) and RT relationship curve (Fig. 5 for single signals, Fig. 7 for multiple).

4) Read the corresponding ordinate RT value for this P(D) as the effect of that environmental level on the switching performance.

5) Repeat steps 1-4 for each environmental level of interest and plot the resulting RT values.

The resulting graph will show RT as a function of environmental-physiological levels with task complexity indicated by separate curves. Environmental performance limits are set at the level which just causes blocking to occur. Since the blocking limit is defined for a given task type as twice the normal RT, a horizontal line drawn from the ordinate RT blocking value will define the region of unacceptable performance on that switching task. Any environmental level which leads to a longer RT than the blocking limit is, thus, defined as undesirable.

(3) Coding

Coding performance is measured by percent correct (%C) categorization of signals. We have assumed (Section V-D) that the percent correct (%C) measure will depend on three factors: (1) the probability of sensory detection, $P(D_S)$; (2) the probability of correct attentional processing, $P(D_A)$; and (3) the probability of correct coding, P(C), which is confounded with a memory factor. If we assume an extremely well-learned task, the memory process may be assumed to be long-term in nature and may be ignored in evaluation of physiologically tolerable environmental effects. Normal coding performance is then described by:

$$(\%C) = 100P(D_S D_A C) = 100P(D_S)P(D_A/D_S)P(C/D_A) \qquad (4)$$

Note that when $P(D_S) = 1.00$:

$$(\%C) = 100P(D_A/D_S)P(C/D_A) = 100P(D_A)P(C/D_A) = 100P(D_A C)$$

If we use the term $P(C/D_A/D_S)$ to denote $P(D_A/D_S)P(C/D_A)$ we, of course, come out with the same result. At some future date we hope to be able to estimate the separate effects of attentional and coding processing on total coding performance. For the present we shall deal with the probability of both correct attentional processing and correct coding, i.e., $P(C/D_A/D_S)$. $P(C/D_A/D_S)$ depends importantly on both the number of signal categories and the duration of signal presentation (see Fig. 9), as well as on any environmental factor influencing any one of the components. Note above that under normal conditions ($P(D_S)=1.00$) the value of (%C) obtained from Fig. 9 is the best estimate of $P(C/D_A/D_S)$ for a given value of N and of stimulus duration.

Using the same logic described for the prediction of environmental effects on search, we may define the environmentally reduced performance as follows:

$$(\%C) = 100\ P(D_S) \left[P(C/D_A/D_S) - P(C/D_A/D_S)(\Delta\ \%B) \right] \qquad (5)$$

The coding prediction curve is obtained by using Eq. 5 in the same manner as Eq. 3 was used for the prediction of effects on searching. As stated earlier, the blocking concept is not defined for coding. To apply the blocking threshold as a limiting condition in this task, it is necessary to determine the threshold in terms of the P(D) value associated with a blocking RT in a switching task which has the same signal characteristics as the coding task.

(4) Tracking

In order to predict a measure of normal tracking performance, as described in Section V-E (Fig. 10), it is necessary to first obtain some estimate of human transmission lag (RT_T). Fig. 11 presents the assumed relationship between (RT_T) and probability of detecting a difference $P(D_d)$ between the target and control output positions. The $P(D_d)$ itself must be a function of the sensory signal detectability, $P(D_S)$, and of the probability of attentional processing, $P(D_A)$, i.e.

$$P(D_d) = P(D_S D_A) = P(D_S)P(D_A/D_S) \qquad (6)$$

Note that this equation is identical to Eq. 3 with the exception of the type of signal to be detected and that the procedures to be used in prediction of $P(D_d)$ differ only slightly from those used for P(D). From Eq. 6 it is obvious that when $P(D_d)=1.00$, both right-hand terms must also equal unity. This requires assuming that $P(D_S)=1.00$ under normal performance conditions, which is consistent with our earlier assumptions. Therefore, for a theoretically or approximately noiseless condition:

$$P(D_d)=P(D_A/D_S)=P(D_A)=1.00$$

Note from Figures 10 and 11 that in the noiseless case $RT_T = .2$ sec. and that performance levels are identical regardless of the kind of control system.

To determine the effect of an environmental factor (or any other factor which influences reception or attention) on tracking, it is necessary to determine the $P(D_S)$ for the condition and to determine the reduction in attentional processing. For the present we shall only predict effects on $P(D_d)$ in a relatively noiseless environment. Using our previous logic, the predicted environmental effect is obtained by:

$$P(D_d) = P(D_S) \left[P(D_A/D_S) - P(D_A/D_S) (\Delta \%B) \right] \qquad (7)$$

The $P(D_d)$ values so obtained, for each environmental level, are then applied to Fig. 11 to obtain the corresponding RT_T value. Figure 10 is then used to predict the actual performance measure.

It was not specifically mentioned, but it is clear that the computational factor is really composed of two factors. First, in tracking, some kind of computation is required to establish the size of the difference; second, a computation is required to determine the size of the corrective action. It seems proper that ultimately the first kind of computation should be included in the factors on which RT_T is assumed to depend. For the present purposes, we have circumvented this issue and have confounded both computational processes in Figure I-10. The computation may be inferred from the differences among the curves.

Tracking presents a unique problem for application of a blocking threshold. Since under noiseless conditions RT_T has been assumed to equal .2 sec., regardless of control level, the blocking threshold will have to be considered as .4 sec. Under most conditions where RT_T is greater than .2 the performance measures for the three control conditions presented in Fig. 10 are identical. However, it does seem reasonable that the higher control levels require more complex computation and a faster rate of processing, and should, therefore, have a lower blocking threshold than lower order control conditions. A more detailed examination of relationships involved in processing during tracking is needed before we can improve on the present statement of the problem.

VII. Concluding Statement for Part I.

This part of the report represents an attempt to develop a systematic approach to the prediction of human performance and to the setting of limiting conditions under varying conditions of environmental stress. We cannot emphasize too strongly that the assumptions made are tentative and intended more to indicate what types of assumption it may be necessary to make than to make well substantiated ones. The same may be said for our decisions about the mathematical models used to combine information represented by the assumptions. A considerably greater examination of the literature of experimental psychology is needed in order to develop basic relationships of greater validity and to develop models for including them.

This part of the report is incomplete also in the sense that we have not yet faced such questions as complex tracking, complex (combined) tasks, and a variety of specific questions of relationships among the underlying processes. As a result, we cannot make even illustrative predictions about some kinds of task. On the other hand, in making our assumptions we have attempted to maintain a consistent point of view (cf Teichner, 1968) about the effects of stress and about the activating and data-handling processes. In addition, we believe that we have applied reasonable constraints to our specific assumptions so that actual predictions can be generated. These may then be evaluated against what data are available in the environmental literature. If it happens that those predictions do make reasonable fits of the data, some confidence can be put into the possibility that we are on the right general track.

Good fits, of course, do not prove anything. But bad fits do; in particular, bad fits indicate a need for revision of the specific assumptions and, perhaps, more. It is hoped that by an iterative process of fitting and revision, and more detailed use of fundamental data, a really useful set of assumptions will emerge.

The following sections represent a sampling of all of the major environmental classes. Part II provides considerable detail, both with regard to the calculational techniques and with regard to the variety of predictions made. Subsequent parts go into no detail about calculational methods since they are the same as for Part II. In all parts are presented a discussion of physiological assumptions and relationships and the actual data available in the literature which seems to apply to the predictions. It will become apparent that such data are, indeed, very sparse. Nevertheless enough exist to provide an evaluation of the general approach and it is with this evaluation that we wish the reader to be concerned. If it appears after evaluation the predictions can be generated which have some resemblance to reality, then we would hope that further work to improve the basis of the predictions would do even better.

TABLE I

TABLE OF TASKS AND THE PROCESSES ON WHICH THEY MAY DEPEND MOST IMPORTANTLY*

TASK		SHORT-TERM MEMORY	ATTENTION	CODING	COMPUTING
SEARCHING:	EXPOSURE OF SENSOR AT DIFFERENT TIMES OR PLACES -- SIGNAL SEEKING. EXAMPLES: MONITORING, RECONNAISSANCE.				
	A) SIMPLE ORIENTING		*		
	B) SUCCESSIVE ORIENTING (SCANNING)	*	*	POSSIBLE	
SWITCHING:	DISCRETE, ACTION WHICH CHANGES THE STATE OF THE NEXT COMPONENT IN A SYSTEM. A) SIMPLE REACTION B) CHOICE REACTION	FOR FAST SEQUENTIAL TASKS.	*	* MINOR FACTOR AFTER LEARNING INCR. W/ NO CHOICES	POSSIBLE
CODING:	NAMING OR IDENTIFYING A DETECTED SIGNAL.				
	A) SIMPLE CODING		*	*	IN SPECIAL CASES.
	B) MULTIPLE CODING	*	*	*	
	C) COMMUNICATION WITH SYNTAX (SUCCESSIVE CODING)	*	*	*	*
TRACKING:	ALIGNMENT OF A RESPONSE WITH A CHANGING INPUT. EXAMPLES: PURSUIT, COMPENSATORY, WALKING, AIMING.	POSSIBLY FOR SLOW AND VERY SLOW INPUTS.	*		*

* NOTE: LEARNING IS ASSUMED TO BE COMPLETE.

TASK	SHORT-TERM MEMORY	ATTENTION	CODING	COMPUTING
COMPLEX TASKS: COMPLEX TASKS CONSIST OF COMBINATIONS OF THE ABOVE. FOR EXAMPLE:				
A. PROBLEM SOLVING: SUCCESSIVE SEARCHING PLUS IDENTIFICATION, PLUS CHOICE REACTION	*	*	*	*
B. READING: SUCCESSIVE SEARCHING, IDENTIFYING, AND TRACKING	*	*	*	*
C. HANDWRITING: TRACKING PLUS COMMUNICATION WITH SYNTAX	*	*	*	*

FIGURE 1-a

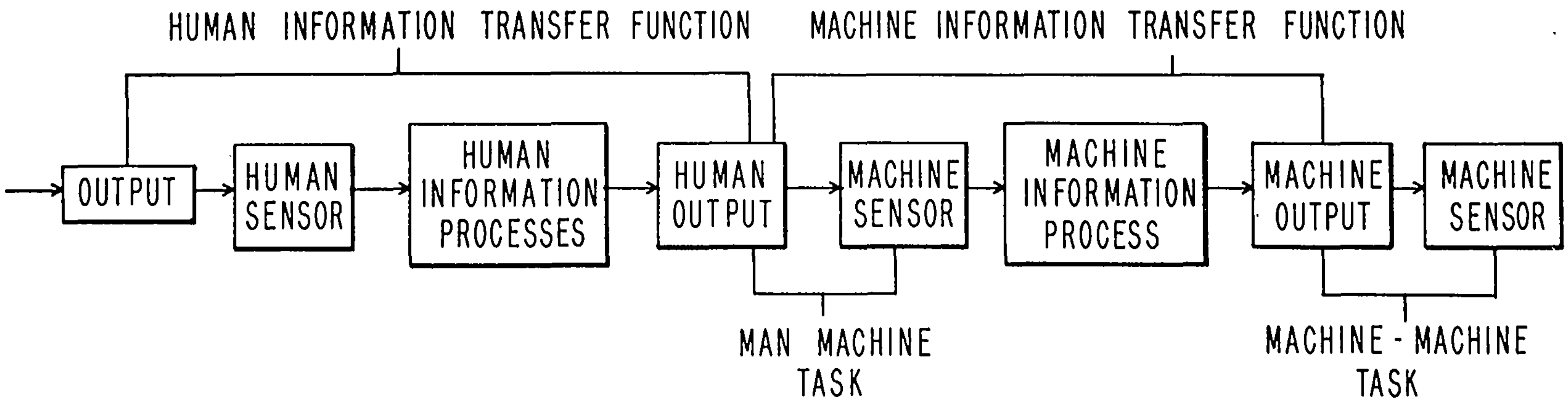

FIGURE 1-b

FIGURE 1. Man-machine system at two levels of description. For simplicity, no feedback loop is shown.

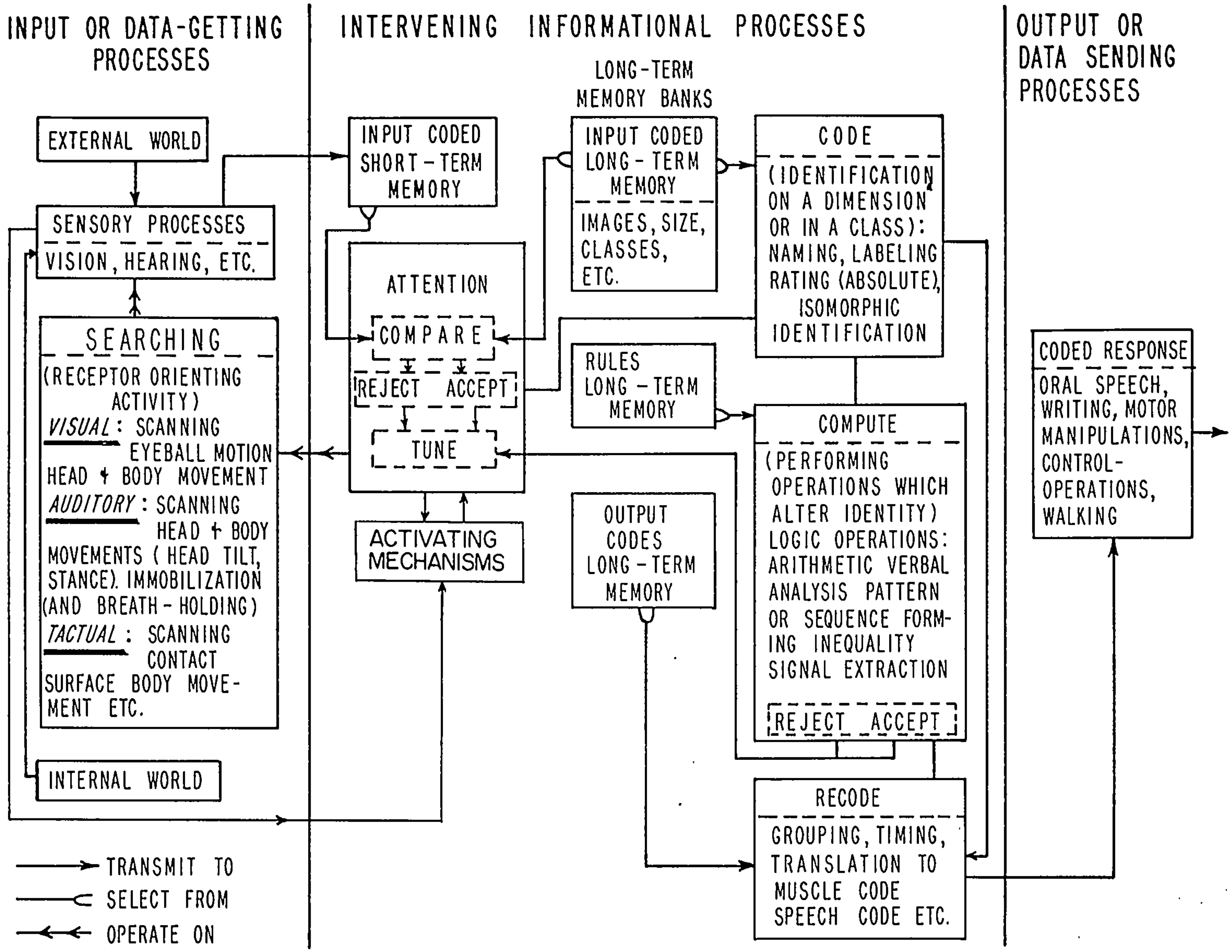

FIGURE 2 Assumed CNS functions and their hypothesized relationships

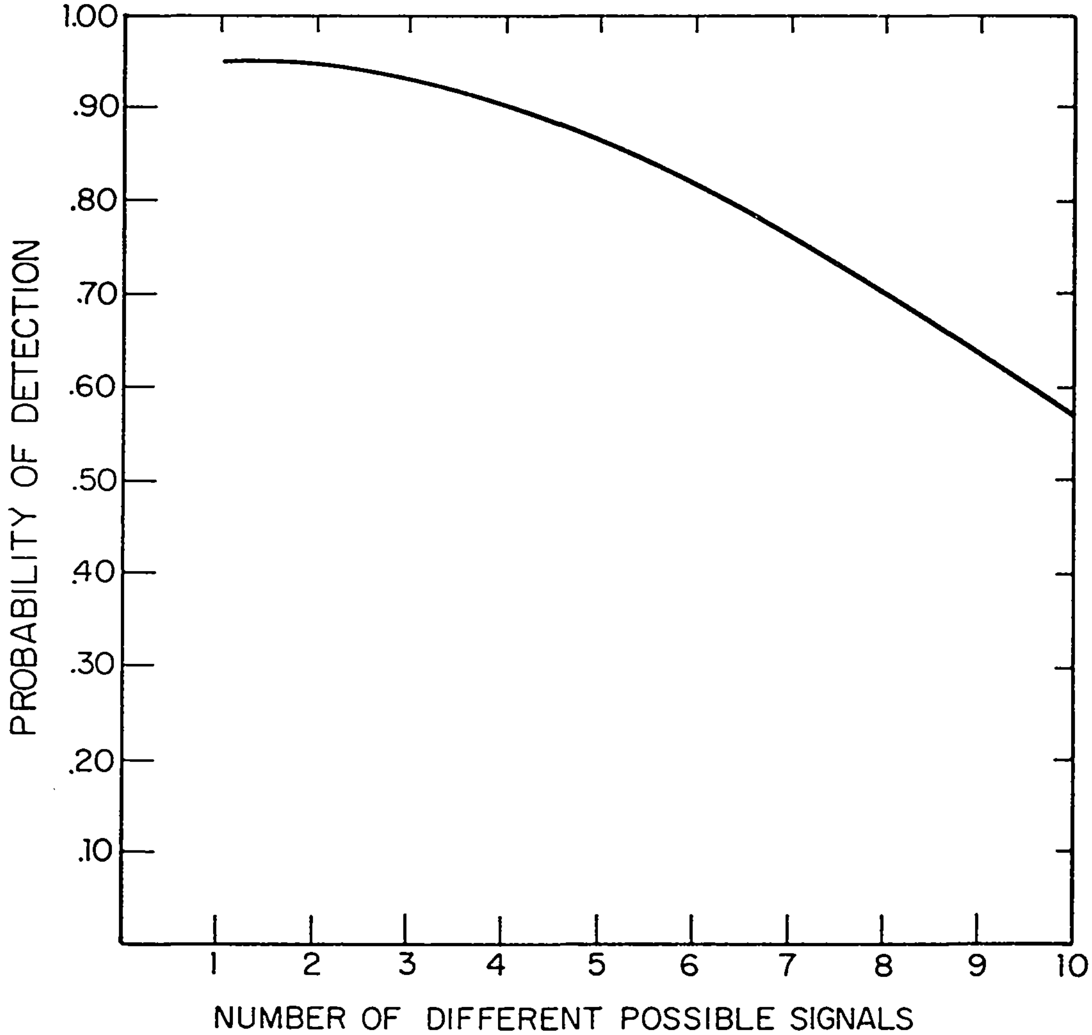

FIGURE 3. Hypothesized detectability of one signal as a function of the number of possible signals.

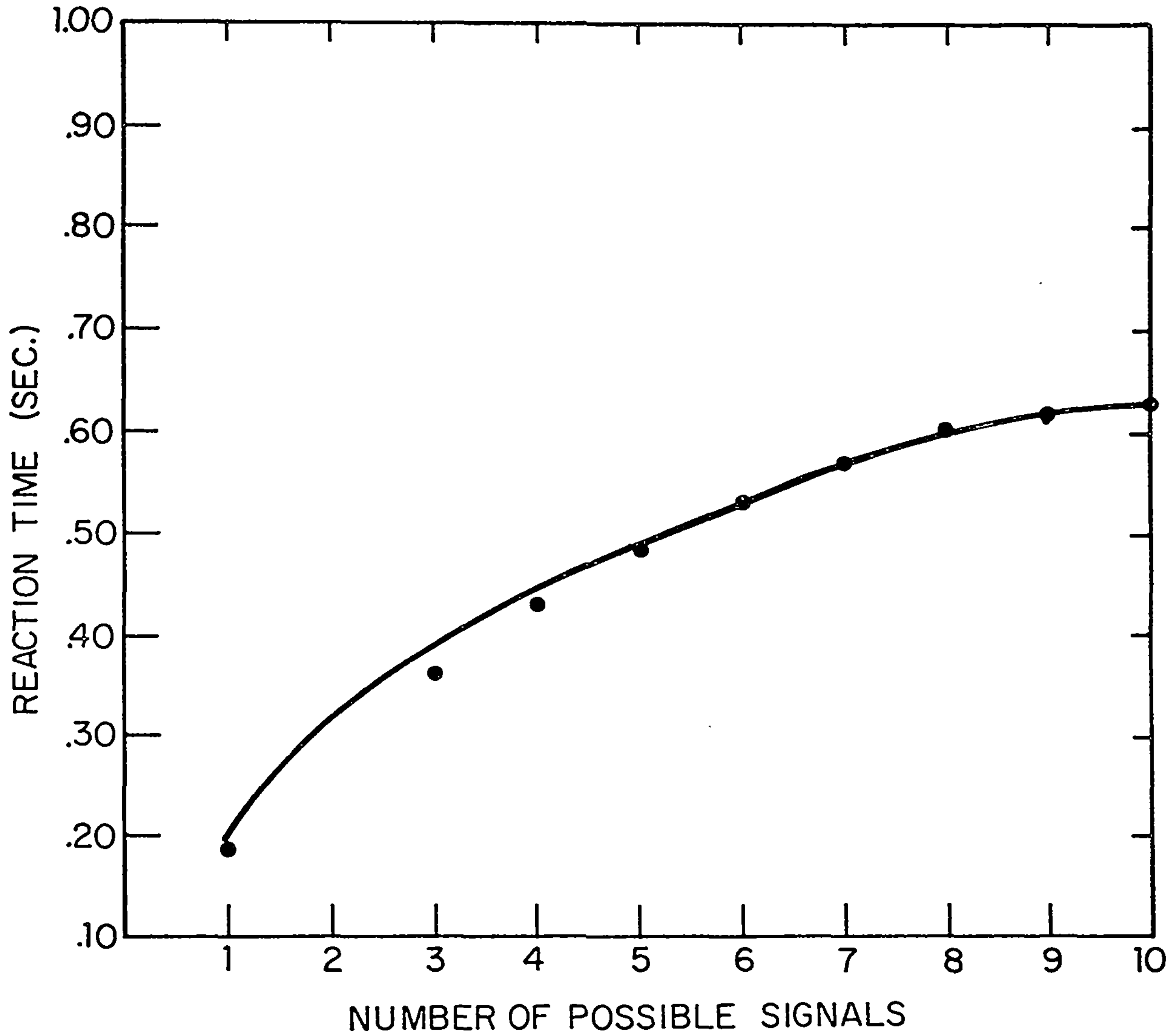

FIGURE 4. Reaction time to one visual signal as a function of the number of possible different signals. Data are from Merkel (1885). The line was fitted with the constraint that reaction time for the one-signal case equal .20 seconds.

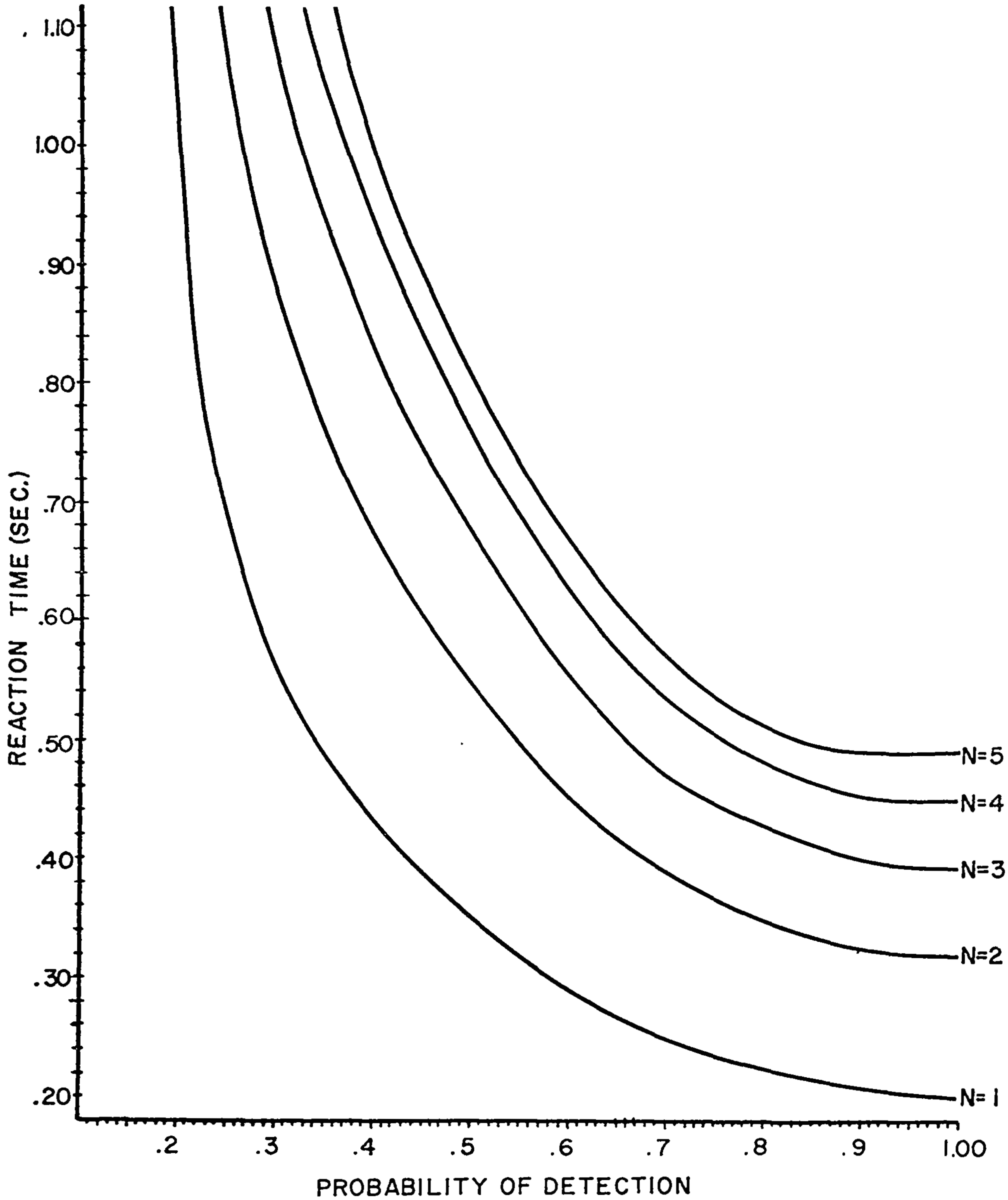

FIGURE 5. Hypothesized reaction time to one signal as a function of signal detectability. The parameter is the number of different possible signals.

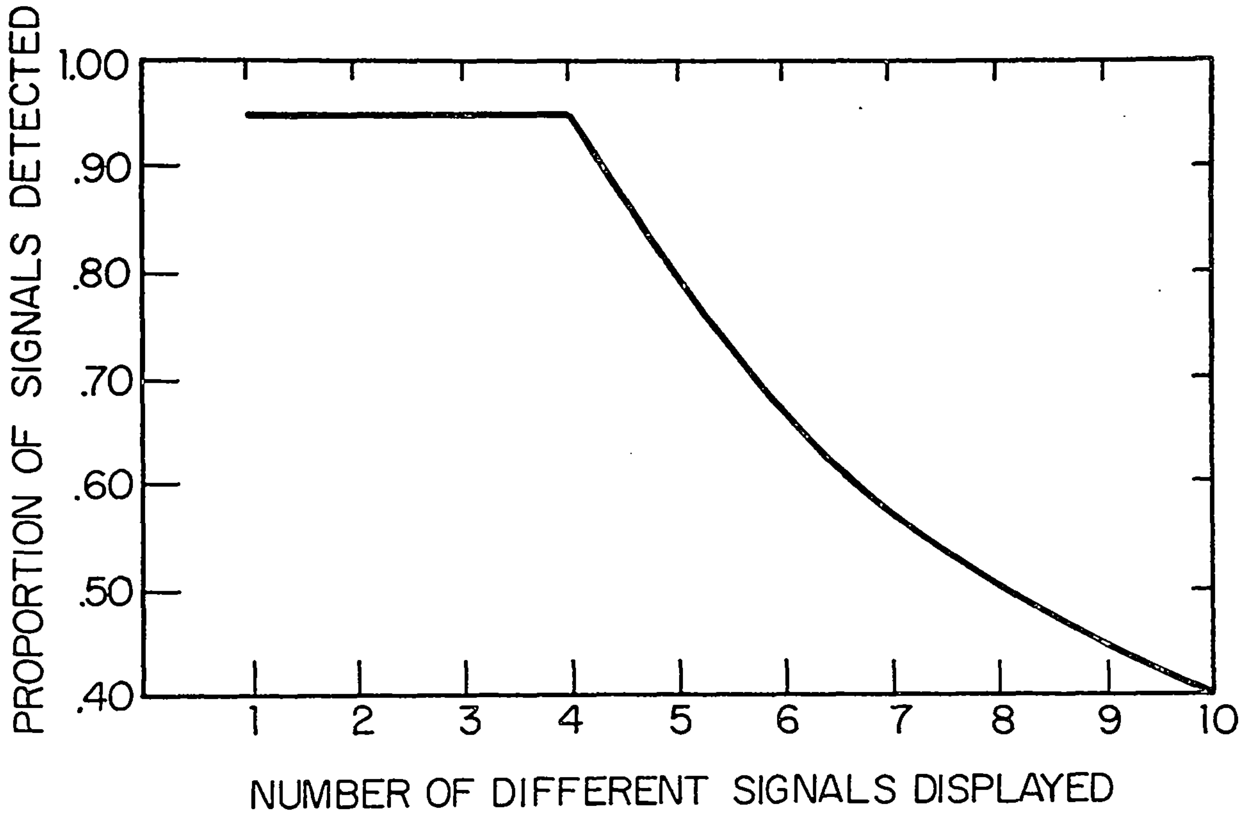

FIGURE 6. Hypothesized multiple signal detection as a function of the number of signals displayed simultaneously. The curve is based on the finding that four signals are the maximum likely to be detected. (Teichner, Reilly and Sadler, 1961)

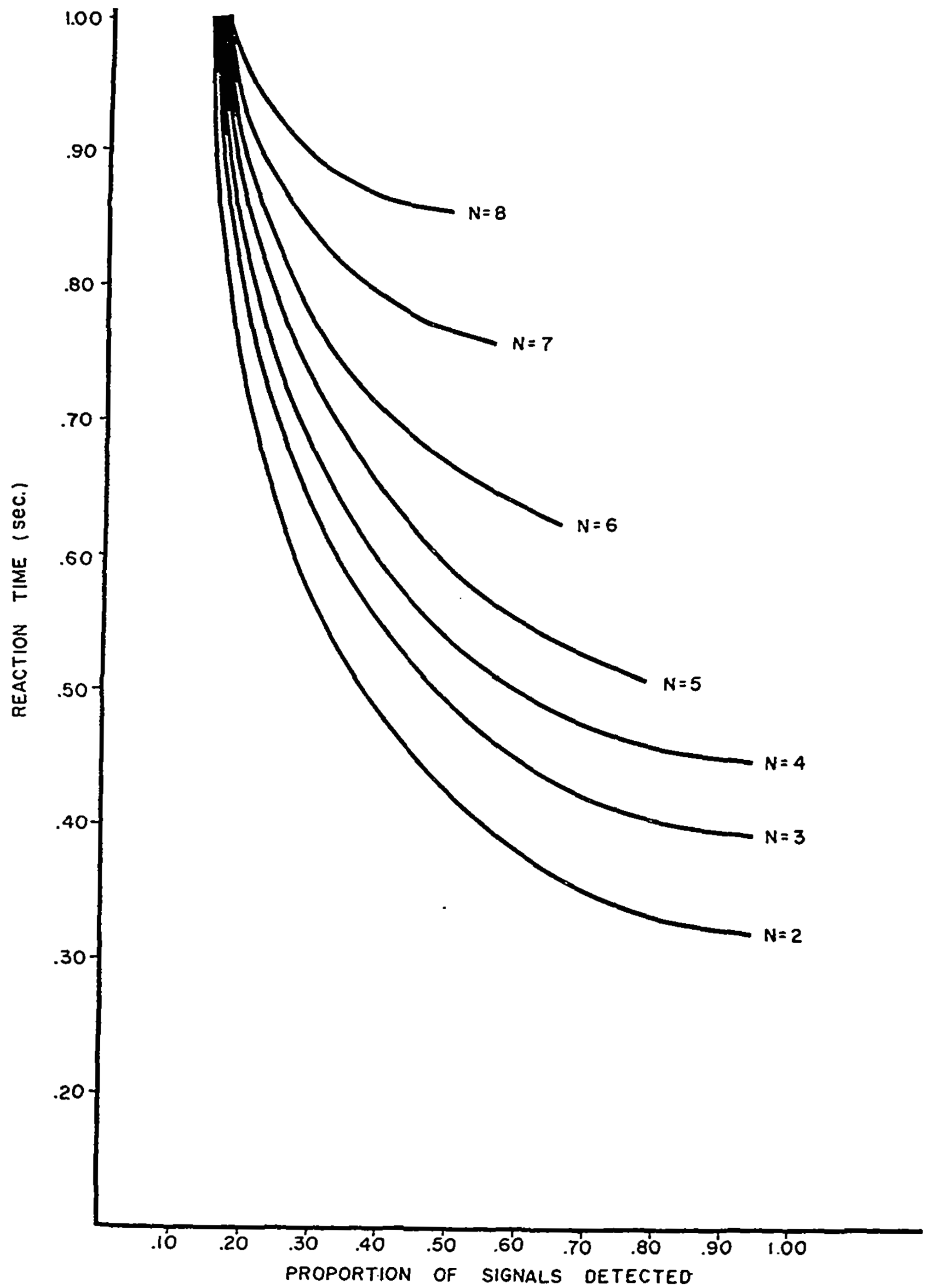

FIGURE 7. Hypothesized reaction time for multiple signal displays. The parameter is the number of signals presented simultaneously. The reaction time is for:
(1) The first reaction of a sequence of responses to the display, or
(2) The time to initiate a single reaction to the signals taken as a combination.

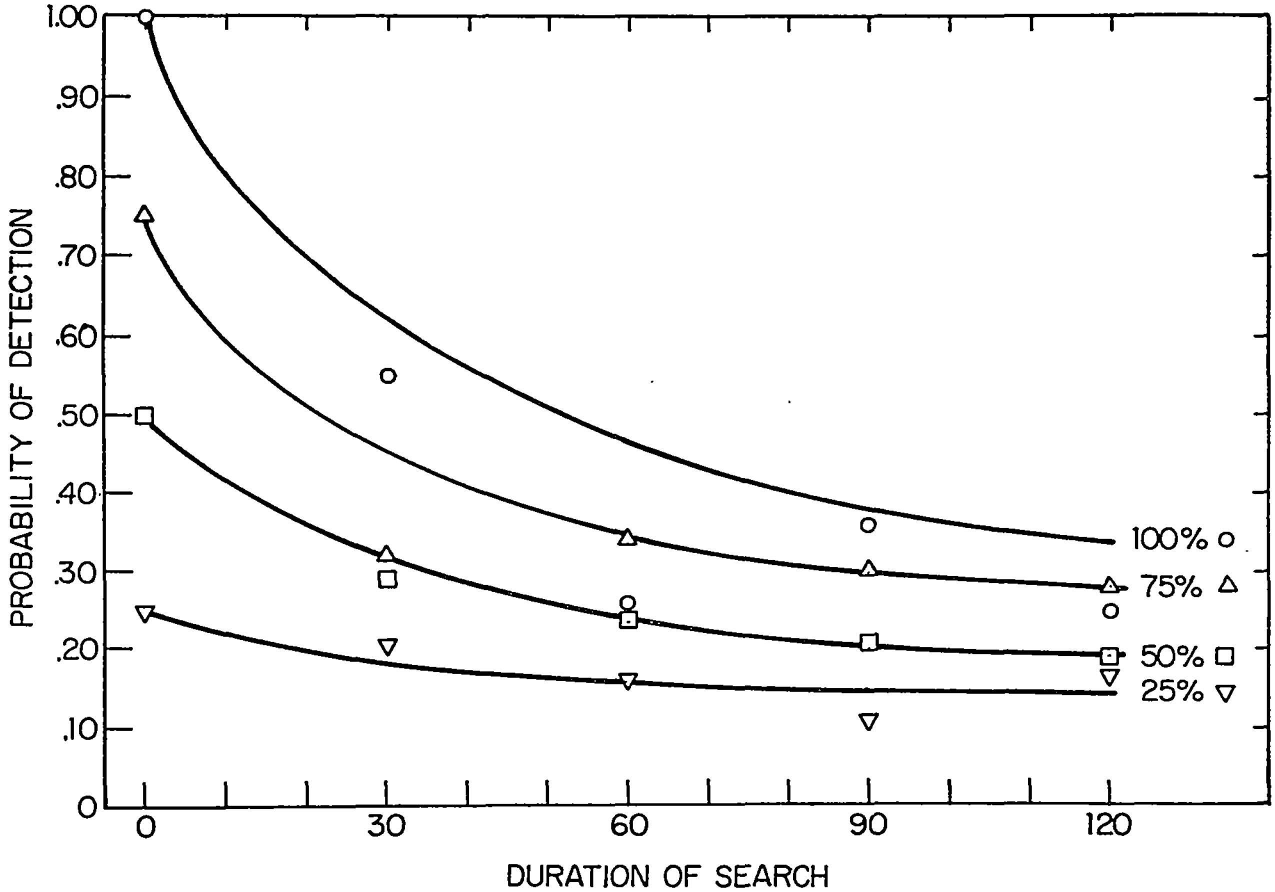

FIGURE 8. Hypothesized visual signal detectability as a function of the duration of search. The parameter is the percent detection of the signal at the start of the search period. Adapted from Teichner, 1962.

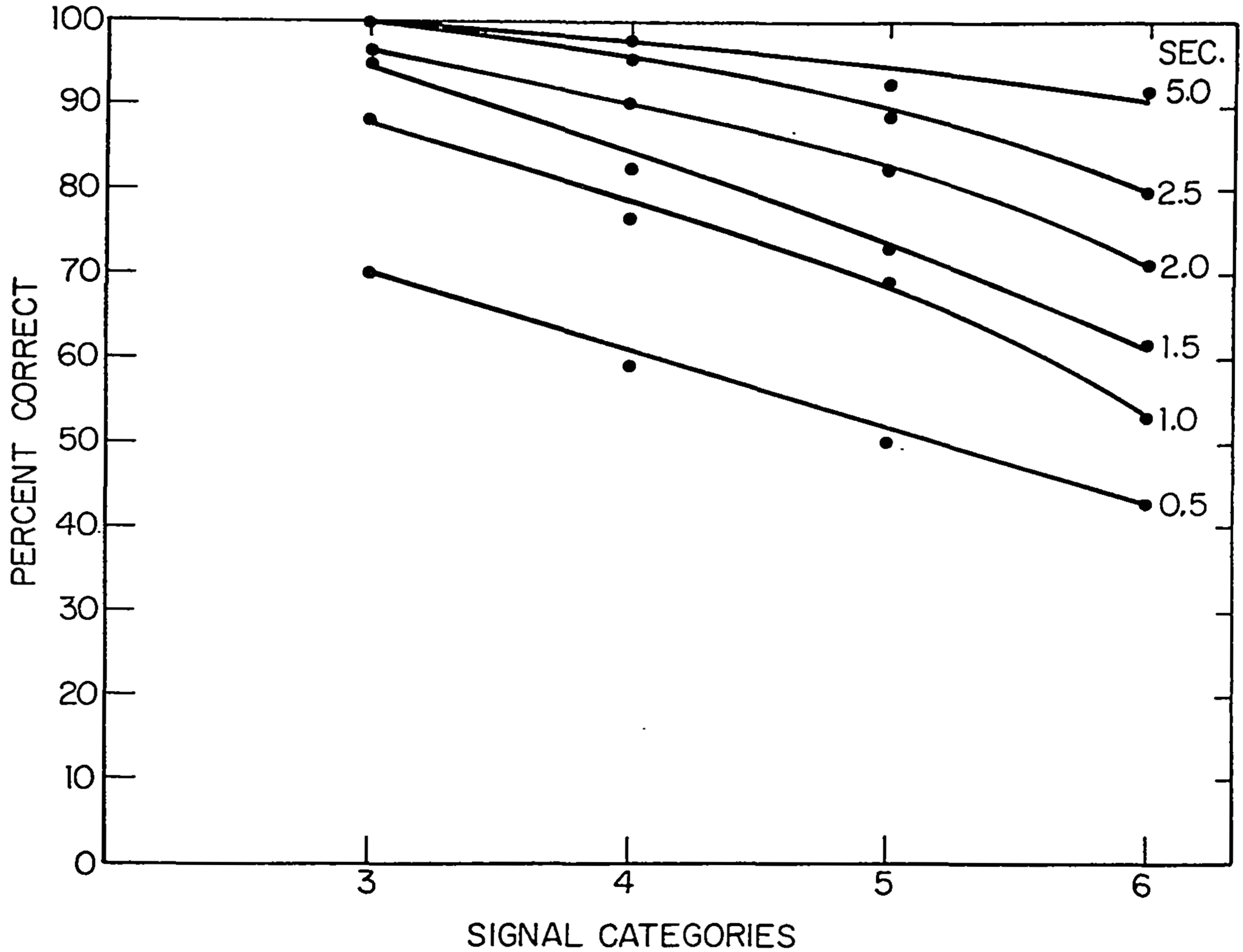

FIGURE 9. Signal coding as a function of number of coding categories. The parameter is the duration of visually-presented displays. From Teichner and Sadler, 1962.

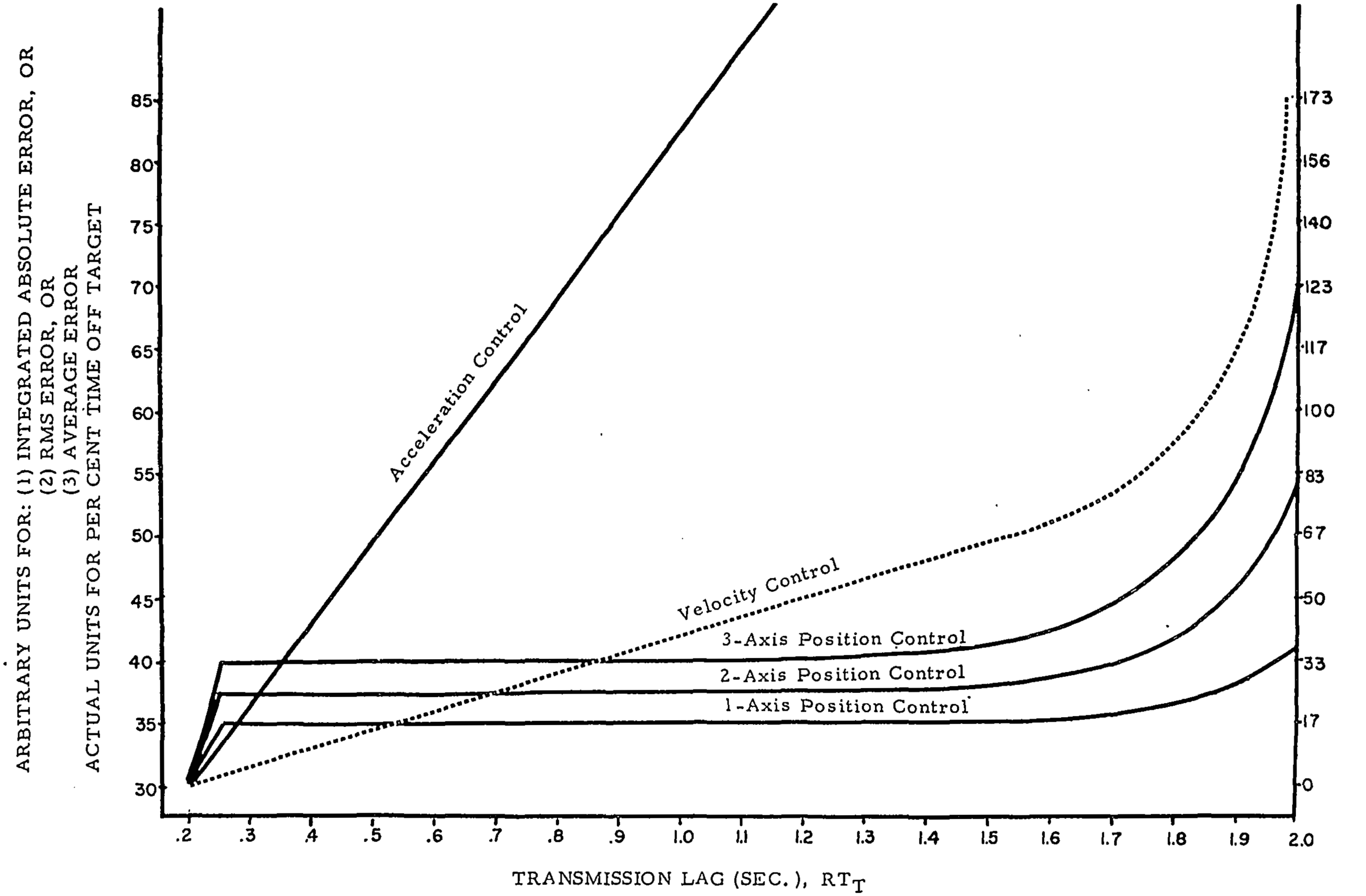

FIGURE 10 Man-Machine System tracking performance as a function of transmission lag and type of control. Note that transmission lag is really the total of the human transmission lag plus machine control lag.

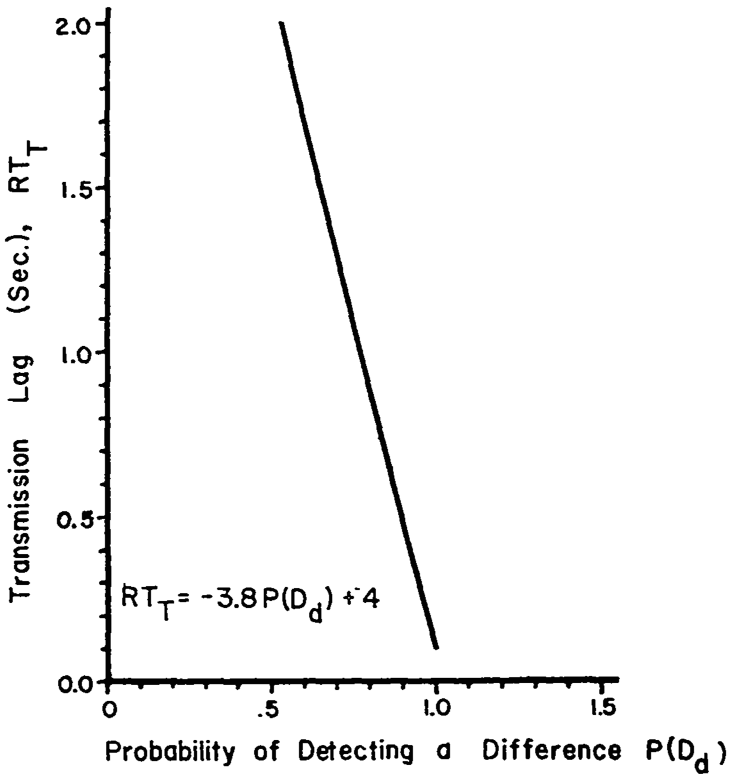

FIGURE 11 Human transmission lag as a function of P(Dd)

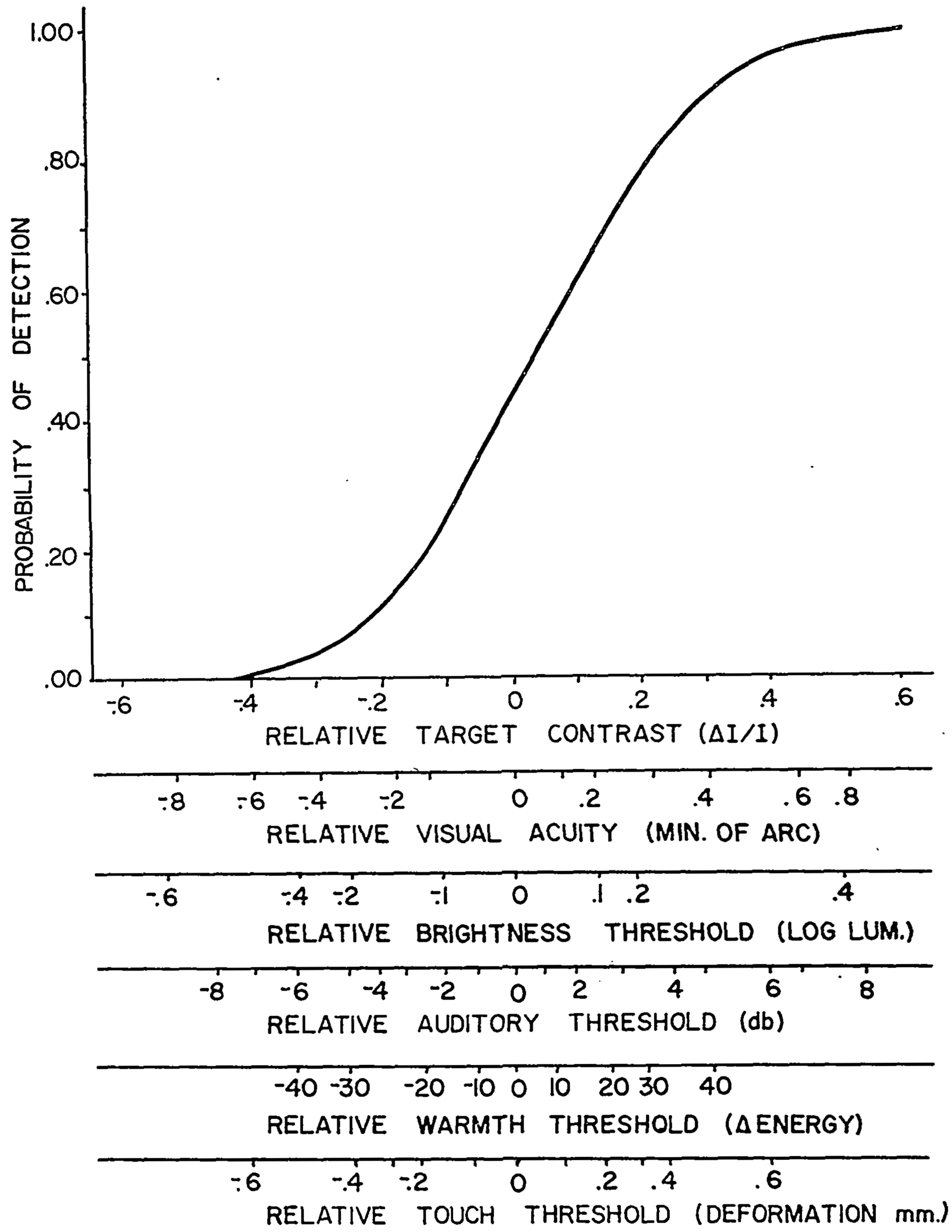

FIGURE 12 Psychophysical probability functions based on various sources. The abscissa values are for the normal deviate from the mean or 50% threshold value (O).

Predicting Human Performance in Space Environments

II. The Atmospheric Environment and Atmospheric Contaminants

The atmospheric environment includes all of those gases and their partial pressures which make up what might be called clean air. Those gases which are physiologically inert, such as nitrogen, are of interest in terms of the effects of increased barometric pressures or of non-normal breathing mixtures. The variable of primary interest, however, is oxygen and for this reason Part II considers the effects of different reduced partial pressures of oxygen in considerable detail. Furthermore, since it is likely that more data are available in the literature which concern the effects of reduced pO_2 than any other environmental variable, consideration of this particular problem provides a useful source for evaluation of the approach.

Atmospheric contaminants may be introduced into the environment from solid sources, or they may be physiologically inert gases in non-normal concentrations, or they may be introduced as a physiological reaction (e.g. flatus, carbon dioxide). Of particular importance to the astronaut environment is the presence of carbon monoxide. In a sense some CO is unavoidable; a critical question, still unresolved, is its effect on performance. Although almost no data exist which show the effect of CO on performance, the immediate and important physiological effects have received considerable study. As will be seen, this prediction problem may be solved by a method which relates performance to those primary physiological effects of CO which are also primary under other environmental conditions. This is particularly important because it provides an additional basis for evaluating the theoretical approach. That is, since hypoxia is a major effect produced by both lowered pO_2 and by increased CO, we shall ask whether we can use predictions generated from pO_2 considerations to the hypoxic equivalents of CO. If so, some support may be gained for the idea that a given physiological state will have an equivalent effect on performance, regardless of its environmental source, so long as it is the concomitant effect of the environment being considered.

I. Physiological and Sensory Effects

A. Physiological Effects of Reduced Oxygen

Studies of the effects of reduced oxygen are of three kinds: altitude studies, studies using pressure chambers, and studies using breathing mixtures containing less than a normal oxygen content. In the latter case most studies have used oxygen-nitrogen mixtures. We shall not consider other possible mixtures and, further, we shall assume that nitrogen is inert under the conditions studied.

Equivalences among altitude, breathing mixtures, and pressure chamber levels have been used for a long time. Most investigators view the use of equivalences with suspicion since for any particular physiological reaction chosen as an equivalence reference, there are others which, if used, would provide different equivalences. Roth and Billings (1964) demonstrated this by showing the different results for equivalent altitudes obtained while breathing 100% oxygen when the reference physiological measure was the alveolar pO_2, the tracheal pO_2, or the blood saturation. Nevertheless, it appears that the consistent use of one of these measures can provide an equivalence standard. We shall use the arterial oxygen saturation for this purpose since it is roughly linear over a wide altitude range.

Figure II-1 presents the relationship between the total barometric pressure and the 0_2 saturation. In addition, the abscissa presents the relationships among barometric pressure, altitude, atmospheric $p0_2$, and aveolar $p0_2$. The data, from various sources, were fitted by eye. Although the curve differs slightly from that developed by Roth and Billings (1964), it agrees closely with that of Van Liere and Stickney (1963). The differences may be due to the inclusion of data not used by those writers. The function may be seen to be positively accelerated and decreasing up to 25,000 feet. For physiological reasons 60 percent saturation can be accepted as a level of imminent collapse of the individual and 70 percent as an unacceptable physiological, or safety, limit. The performance effects of primary interest, therefore, are those which occur at saturation levels above 70 percent.

B. Physiological Effects of Carbon Monoxide

Since the hemoglobin has a much higher affinity for CO than for 0_2, CO acts to reduce the oxyhemoglobin. Figure II-2 shows the relationship between the CO concentration in air and the COHb at equilibrium. This figure from Larsen (1966) also provides a variety of standards in current use. Figure II-3, also from Larsen, shows the interrelationships among the CO concentration, the percent of hemoglobin unavailable for 0_2 transport, the equivalent altitude, and time of exposure as a parameter. The data apply to individuals involved in light physical activity.

C. Use of the Physiological Measures

We shall assume that the effects of CO and of reduced pO_2 are the same for the same level of hypoxia expressed as percent arterial O_2 saturation. The base of performance prediction figures to be used will provide this measure as an abscissa and, in addition, will present the equivalent levels of pO_2 in O_2-N breathing mixtures, the pBO_2, the percent COHb, and the CO concentration in air in parts per million. Thus, both the engineering information and the physiological information are available for conversion. The blood saturation is the reference measure and, therefore, it will be necessary to obtain performance relationships in terms of this reference.

D. Visual Effects of Hypoxia

Our derivations are based upon the parameters which determine target detection. However, data are available which show the effects on other visual processes; they are included here for supplemental use if desired. Figures II-4, II-5, and II-6 respectively show the effects of reduced blood saturation on visual flicker fusion level, increase in scotoma, and the increase in the latency of the visual after-image.

Figures II-7, II-8, and II-9 show the effects of the environmental-physiological conditions on the absolute sensitivity to light (brightness threshold), on contrast sensitivity, and on visual acuity. All curves were fitted by eye. All three represent the increase in the visual factor (contrast, brightness, size) required to maintain a threshold of 50 percent detection.

Figure II-10 presents the effects of CO on brightness sensitivity. At the same time it allows for a comparison of these points with the fitted line of Figure II-7. As may be seen the line overestimates the points somewhat, but the duration is fairly constant and not very large. Inspection of Figure II-7 suggests that the differences between studies is likely to be fairly large. For example, the CO data points would be closer to the points of Figure II-10 than would that of Wald et. al. (1942) which would be farther away than the fitted line. Considering the variability, and the fact that the data of Figure II-10 appear to be the only relevant data available for CO, it was decided to use the fitted line as the best estimate of the effect for both CO and reduced O_2. The small discrepancy in fit appears to warrant this procedure. As a result, from this point of discussion and on, the effects of these two environmental conditions are treated as identical.

Since all of the sensory data are expressed in terms of the 50 percent threshold, it is necessary to make conversions to 98% as described in Part I. The ogive presented in Section I is used for this purpose, and is repeated here as Figure II-11. An explanation of how conversions to 98% are made will be given in terms of an example. First, referring to Figure II-8, at a blood saturation level of 75%, it can be seen from the fitted line that the contrast must be increased by .28 to maintain the 50% threshold. Using this threshold as zero in Figure II-11, and reading the abscissa at -.28, shows that if the contrast were not increased by that amount the probability of visual signal detection would decrease to .08. That is, there would be a loss of (.50-.08) = .42 in the probability of detection. Taking .98 as representative of an easily detectable signal, (.98-.42) = .56 which is the probability of detection of a normally easily detected contrast at a blood saturation of 75%.

When the kind of calculation described is extended across the range of Figure II-8 and then carried out for Figure II-7 and II-9, three functions are obtained. Each represents a characteristic of a visual target which may be used for detection of that target. The probability of sensory detection of the target by at least one of these characteristics, $P(D_S)$, is calculated by using Eq. 1, repeated here for convenience:

$$P(D_S) = 1-(1-P_1)(1-P_2) \ldots (1-P_n)$$

In this example P_a, P_b and P_c will be used to denote the respective probabilities of detecting the target based only on (a) size, or (b) brightness, or (c) contrast. Then:

$$P(D_S) = 1-(1-P_a)(1-P_b)(1-P_c).$$

Figure II-12 presents the results of the calculations. It can be seen that, according to the models used, the probabilities of detection for each target characteristic decrease rapidly with decreasing blood saturation. It is of passing interest that at 70% saturation, these probabilities would be approximately 50%. In spite of these decreases, the figure shows that the probability model predicts a slow decrease in target detectability so that at 60% saturation, the probability of sensorially detecting a signal is still .72.

II. Effects of Hypoxia on Attention

Bills (1937) studied the effects of varying O_2-N breathing mixtures on response blocking. Both the frequency of blocks and the duration of blocks increased systematically as the percent O_2 decreased. Figure II-13 presents Bills' data transformed to the percent increase in frequency and in duration of blocks using his normal air content as a reference. The frequency curve is presented for general interest. The duration curve serves as our estimate of the effect of hypoxia on the attentional process.

III. Predicted Effects of Environment on Performance

This section presents our predicted performance curves as a function of hypoxia levels. The methods and equations, as well as underlying assumptions, used in deriving predictions are explained in detail in Part I, Section VI-D. Equations are repeated here; however methods are repeated only in summary form.

Wherever we have found useable data the points have been superimposed on our prediction curves. It will be noted that very few data points are plotted. Although there are some hypoxia studies which utilize performance tasks, most of these fail to present useable data for one of the following reasons:

1) Lack of adequate methodology causing confounding of experimental variables.
2) Lack of adequate specification of the environmental levels associated with performance, usually due to failure to take concomitant physiological and environmental measures.
3) Lack of adequate description of task procedures leaving doubt about: (a) time at environment; (b) stimulus-response parameters; (c) time involved in task performance.
4) Use of measures which require tedious transformations in order to be comparable to usual performance measures.

Wherever possible we have attempted to plot data even when lacking in a critical characteristic, e.g., no specification of time at task. Even making these concessions, we cannot plot many points because the few reasonable studies existing present isolated data points rather than empirical functions.

Therefore, in most cases we present these prediction curves mainly to illustrate the prediction procedures, to emphasize the lack of data, and to suggest the parameters to be incorporated in future studies on hypoxia.

A. Searching

(1) Search for one possible signal

In Part I (Section V-A) we presented the rationale for assuming that the sensory detectability, $P(D_S)$, is the best estimate of performance for a search task where only one signal is possible and where that signal arrives in a known position, but at an unknown time. Thus, Figure II-12, presenting $P(D_S)$ as a function of arterial oxygen saturation (% Art. O_2), gives the predicted performance on this task at various hypoxic levels.

If the task is performed for relatively long durations, as in the usual vigilance experiment, there is assumed to be an effect on attentional processing; the reduced P(D) values are then derived from Figure II-8 (or Appendix B). Figure II-14 presents the obtained curves for the combined effects of hypoxia and time at task. Note that performance is predicted to drop considerably when the task is performed for 30 min.

Figure II-14 also shows two physiologically unacceptable zones, discussed above, and an unacceptable behavioral zone. The latter was obtained from Figure I-5 by finding the probability of detection equivalent to that reaction time which is twice normal for the N=1 line, i.e. RT = 2(.2) sec. or .4 sec., and P(D) = .435.

Search involving the detection of one signal given that the signal could be any one of N, involves both sensory and attentional processes. The predicted effect at a given environmental level is calculated as described in

Part I (Section VI-D) using Eq. 3:

$$P(D) = P(D_S) \left[P(D_A/D_S) - P(D_A/D_S)(\Delta \%B) \right]$$

Where $P(D_S)$ is obtained from Figure II-12, $P(D_A)$ is estimated by the normal P(D) value in Figure I-3, and $(\Delta\%B)$ is obtained from the blocking duration curve of Figure II-13. The resulting plot of P(D) as a function of arterial oxygen saturation is shown in Figure II-15 for N=1-5 possible signals. The N=1 curve represents search for one possible signal arriving at both an unknown position and time. The blocking thresholds were obtained using Figure I-5.

Figures II-16, II-17, and II-18 respectively show the additional effects of search time for N=1, 2, and 5 possible signals. The values for each of these curves was obtained by considering the P(D) values in Figure II-15 as initial probabilities to be entered into Figure I-8.

(2) Search for multiple signals

Under normal conditions the proportion of N simultaneous signals detected is based on Figure I-6. Environmental functions are then obtained in a manner comparable to those used for the other search task variants. At a given environmental level and for a given value of N the predicted P(D) is obtained as before by using Eq. 3:

$$P(D) = P(D_S) \left[P(D_A/D_S) - P(D_A/D_S)(\Delta \%B) \right]$$

The $P(D_A/D_S)$ value for multiple signals is estimated from Figure I-6. Figure II-19 presents the obtained predictions for N=2-8. Note that the prediction curves for N=2, 3 and 4 are identical since Figure I-6 is flat at these values. The test of this assumption remains to be made since no data are readily available. The unacceptable behavioral limits were obtained using the appropriate valued N-curve in Figure I-7. These limits differ for N=2, 3 and 4 because the same P(D) value is associated with different RTs depending on N.

Search as a function of both hypoxia and time at task were obtained, as before, by treating the P(D) values of Figure II-19 as initial probabilities of detection in Figure I-8. The results of these operations are shown in Figures II-20 anc II-21 for N=2, 3, 4 and N=5 signals respectively.

B. Switching

Once hypoxic search performance has been developed as a set of predictions, switching performance becomes easy to establish. The measure of performance is the time from signal onset to initiation of a switching response (RT). For the various possible task complexities, RT has been assumed to be completely determined by P(D).

To predicthypoxic switching performance on tasks involving single signal presentations, the P(D) values are obtained from Figures II-14 to II-18; these values are then entered into Figure I-5 to provide a comparable set of switching predictions as shown in Figures II-22 to II-26.

To predict switching on tasks involving multiple signal presentations, the P(D) values are obtained from Figures II-19 to II-21 and are entered into Figure I-7 to obtain the switching predictions shown in Figures II-27 to II-30. Note that although the P(D) values are the same for N=2, 3 and 4, the use of Figure 7 yields different RT predictions curves.

The few studies available have provided only isolated data points rather than empirical curves. Most of the data were obtained by some type of averaging over time,although they seldom involved long times at the task. For this reason, wherever times are not presented we have corrected the obtained data to equate the normal performance level to our predicted normal performance level at time = o. In Figure II-22 three simple RTs are shown, each from a different study involving quite different testing conditions. In this case .20 second is the expected RT under normal conditions. To illustrate the correcting procedure, since the control point from Waldfogel (1950) was .204 second, .04 (=.200-.204) was subtracted from Waldfogel's test point. The three corrected points all nicely follow the prediction of little change in simple RT for a short duration task as a function of arterial O_2.

The only other switching data available are for N=5, shown in Figure II-25, from McFarland, 1937. The two points shown are corrected as just described. One represents the average result obtained from two unacclimatized subjects; the other from six partly acclimatized subjects. As expected, the partly acclimatized subjects performed slightly better. It is interesting that the predicted values represented by the smooth line passes between and close to both points.

C. Coding

Coding performance is measured in terms of percent correct (%C) response selection. The basic function, as presented in Figure I-9, depends on the stimulus duration as well as number of coding categories (N). The environmental effect for a given value of N and stimulus duration is predicted by Eq. 5:

$$(\%C) = 100P(D_S) \left[P(C/D_A/D_S) - P(C/D_A/D_S)(\Delta\%B) \right]$$

where $P(C/D_A/D_S)$ is estimated from Figure II-9, $P(D_S)$ from Figure II-12, and $(\Delta\%B)$ from Figure II-13. Prediction curves so obtained are shown in Figure II-31 for N=3 and 5 at two duration times = .5 and 2.0 second.

Figures II-32 to II-35 present our tentative predictions for the combined effect of hypoxia and time at task for the four curves in Figure II-31. These curves were obtained by treating %C/100 as though it were a P(D) value in Figure I-8.

It may be noted that no behavioral limits were drawn on the predicted coding curves. Response blocks, as explained in Part I-VI, are not defined for the coding measurement. We have suggested that limits be set on the basis of the limiting P(D) value for a search task with similar stimulus characteristics. This requires describing whether the coding required single or multiple signal detections; the former would suggest the use of Figure I-5 to set limits, while the latter suggests Figure I-7.

Although there are some "coding" data in the hypoxia literature, the experimental tasks either: (1) differ remarkably from our definition of coding (e.g., some cancellations), (2) involve much more complex coding than we have yet predicted, or (3) present data in time measures. In any case the signal durations are seldom given. Since the type of coding we have described occurs often in spaceflight performance tasks, we strongly recommend designing parametric studies on coding for all space-relevant environments.

An analysis of the CO literature shows few human performance data of any kind. Schulte (1963) presents the only human coding data for this environment. Although we are unable to plot his data in terms of percent correct coding, we may use the study to indicate what CO levels affect coding. The data indicate that 5% CO Hb (90% Art. O_2) leads to a detectable effect on both color and letter coding performance. Note that our prediction curves just start to decrease at 5% CO Hb.

D. Tracking

The assumed relationships between various tracking measures and human transmission lag (RT_T) are presented in Figure I-10 for three levels of position control and for acceleration or velocity control. At the present we shall only be concerned with position control. Note that the percent-increase-in-error ordinate assumes 30% time-off-target under normal performance conditions; if this is not the case, for a given tracking task the ordinate should be adjusted to another assumed normal level of performance. RT_T has been hypothesized to be a function of the probability of detecting a difference between target and control (or desired) output positions, $P(D_d)$, as shown in Figure I-11. The reader is referred to Part I, Sections V-E and VI-D, for a more thorough explanation of the underlying assumptions for the figures and equations to follow.

At a given hypoxic level, the effect on $P(D_d)$ is then predicted by Eq. 7:

$$P(D_d) = P(D_S) \left[P(D_A/D_S) - P(D_A/D_S)(\Delta \%B) \right]$$

where $P(D_S)$ is estimated from Figure II-12 and (Δ %B) from Figure II-13. $P(D_A/D_S)$ is estimated by the normal value under noiseless or approximately noiseless conditions (=1.00). Each predicted $P(D_d)$ value is then applied to Figure I-11 to obtain the associated RT_T. A plot of the predicted RT_T at each hypoxia level is shown in Figure II-36. The predicted measure of tracking performance is then found by applying each RT_T value to Figure I-10, and plotting the obtained measure as a function of hypoxia as in Figure II-37.

We have found three studies which give data for a one-axis position control, pursuit tracking task (Barach, et. al., 1943; Green, 1947; and Dugal and Fiset, 1950). Green (1947) and Dugal and Fiset (1950) used error measures. Since we have assumed 30% time-off-target associated with normal performance, or zero percent increment in error, we have plotted these data in terms of our norm. For example, Dugal and Fiset's results indicate a 15% increment in error at 10,000 feet altitude (88.25 % Arterial O_2); thus, (.30)(.15) = .045 or the absolute increment in error expected, and (.30) + (.045) = .345 or 34.5% expected time-off-target is associated with a 15% increment in error. Note that this plotted value falls very close to the predicted. Green's data fall just below the two-axis line, but his point is still lower than the plotted two-axis data.

We have transformed any percent time-on-target data to percent time-off-target, also assuming our normal value (70% time-on-target). For example, Barach et. al., (1943) found an 8% decrement in time-on-target at 78.5 % Arterial O_2. Then, (.70)(.08) = .056 or the absolute loss in percent on target, and (.30) + (.056) = .356 or 35.6% expected time-off-target for 8% loss in time-on-target. The plotted point is again close to the predicted value.

Two-axis position control data were obtained from Scow et. al., (1950) and Figarola and Billings (1966). Both studies presented tracking measures in terms of percent increase in error. Thus, the same adjustment was made as for Fiset and Billings' data. Although Figarola and Billings' point at a high percent O_2 is lower than predicted, the plotted points for low O_2 levels fall close to the predicted performance line.

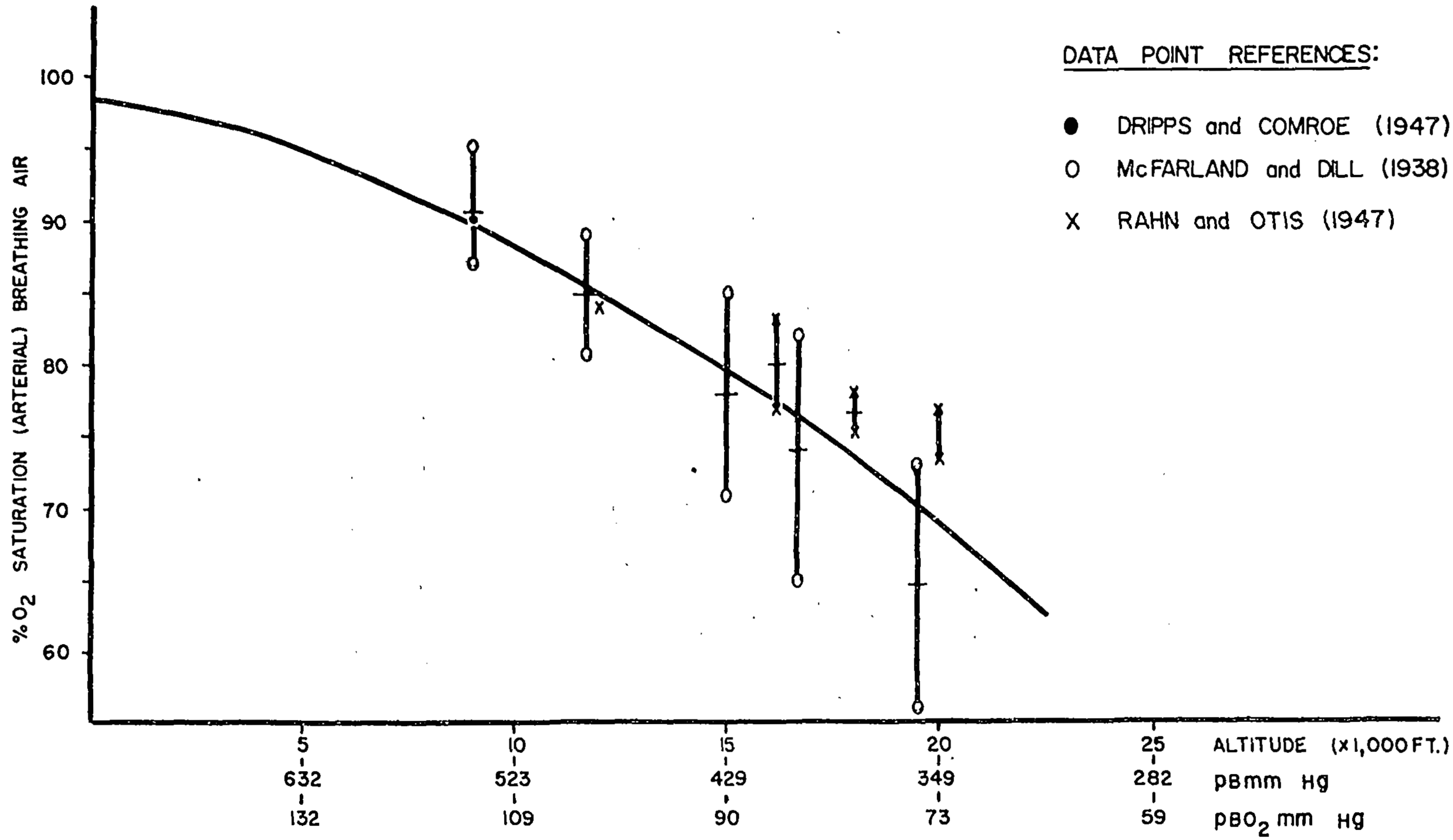

FIG. II-1 Mean Brachial Arterial O_2 Saturation (%) in Unacclimatized Subjects, at Rest or Light Work at Various Altitudes. Adapted from Teichner, Craig and Tompkins, 1966.

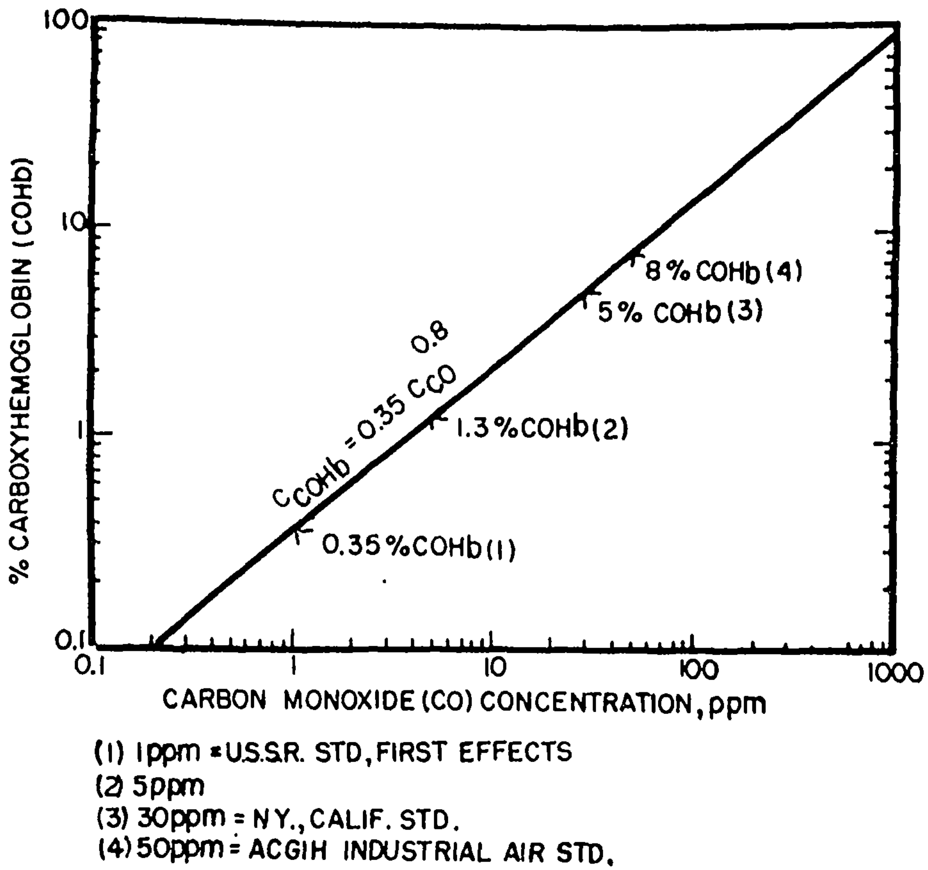

FIG. II-2 Percent COHb as a Function of CO. From Larsen, 1966.

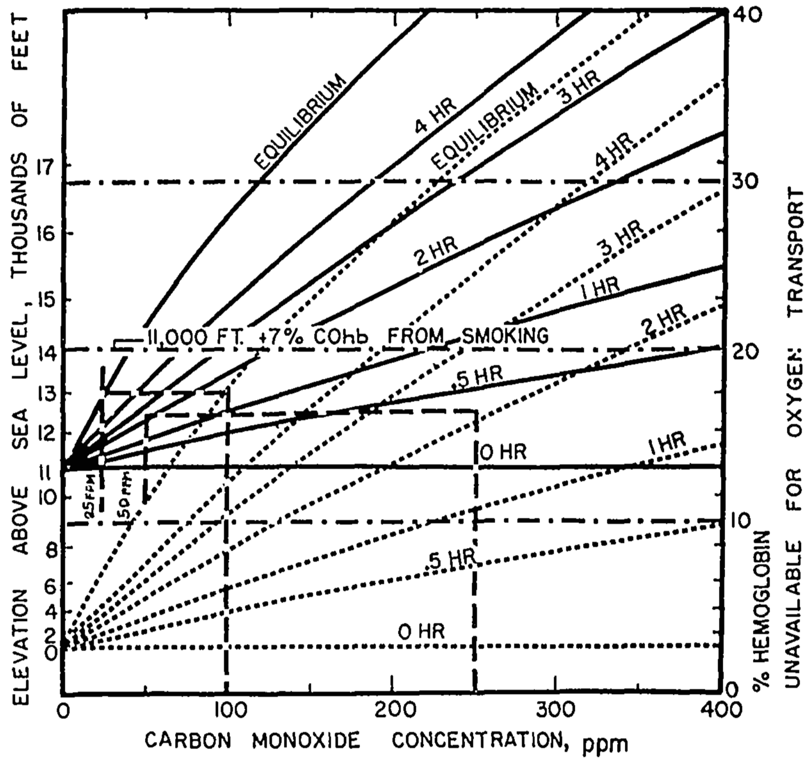

FIG. II-3 CO as a Function of Altitude and COHb at Various Durations at Environment. From Larsen, 1966.

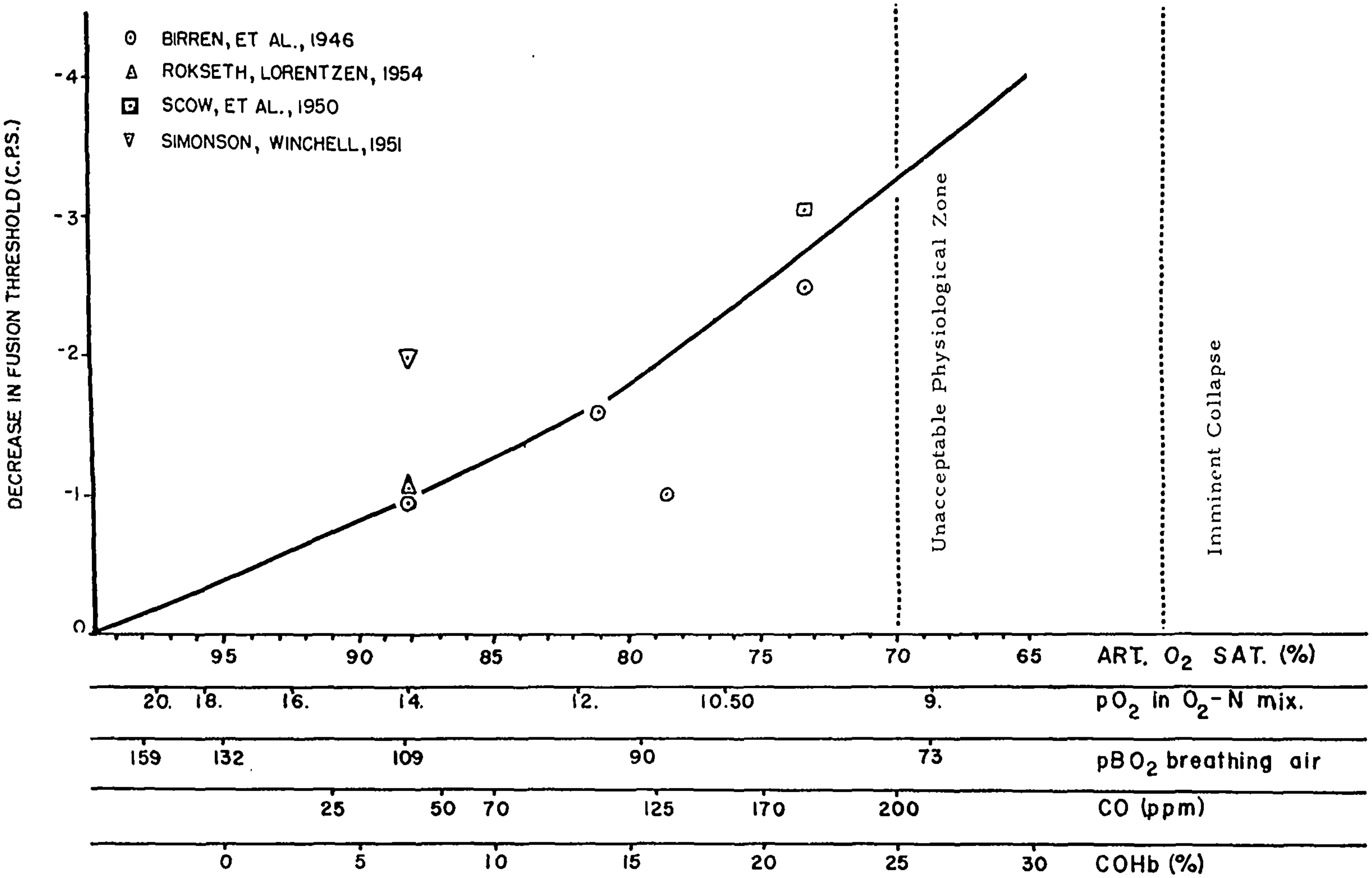

FIG. II-4 Decrease in Flicker Rate Required to Prevent Fusion 50% of the Time as a Function of Hypoxic Level.

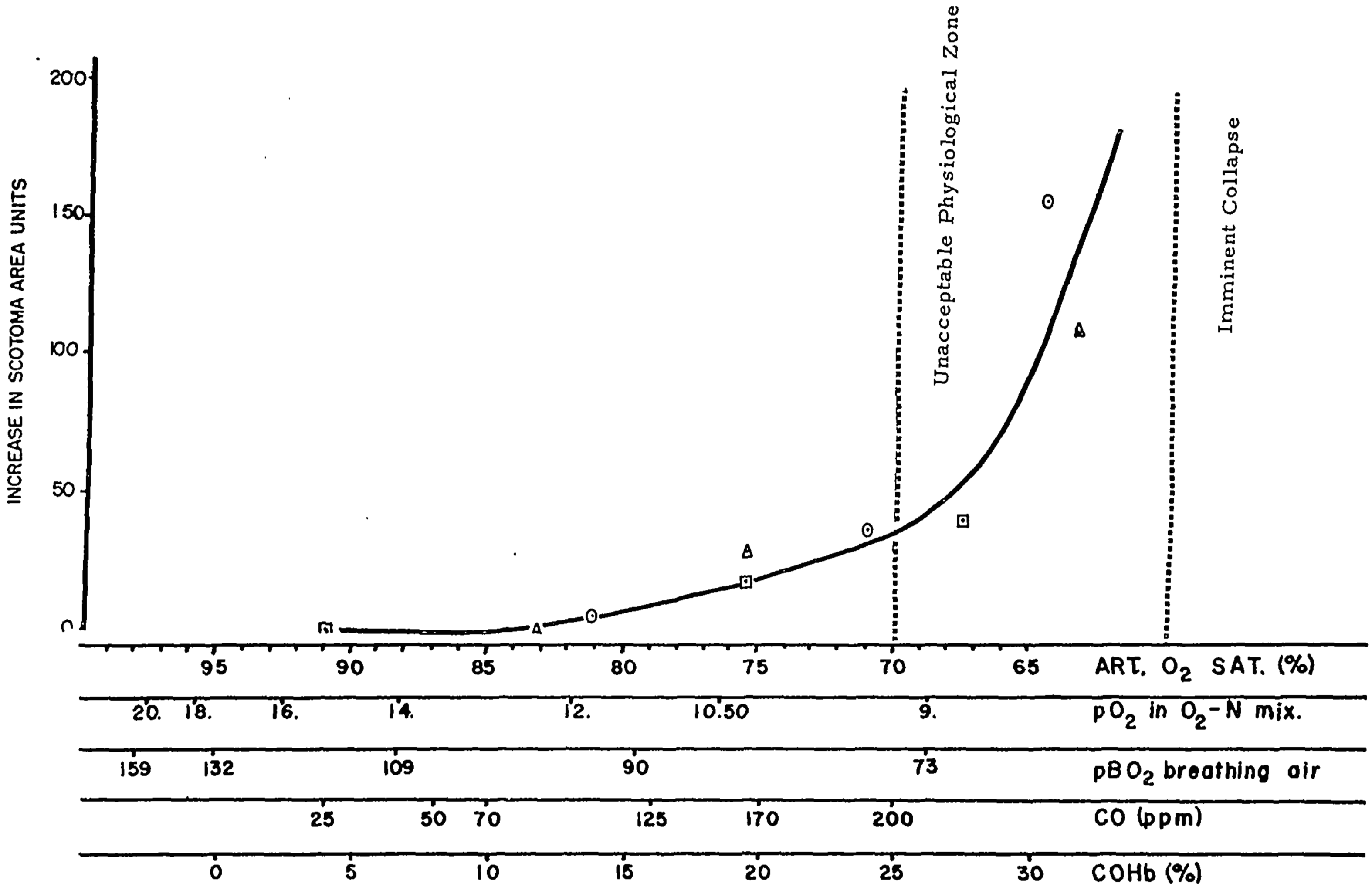

FIG. II-5 Effects of Hypoxia on Increase in Scotoma Area. Data from Evans and McFarland (1938) Based on 3 Subjects.

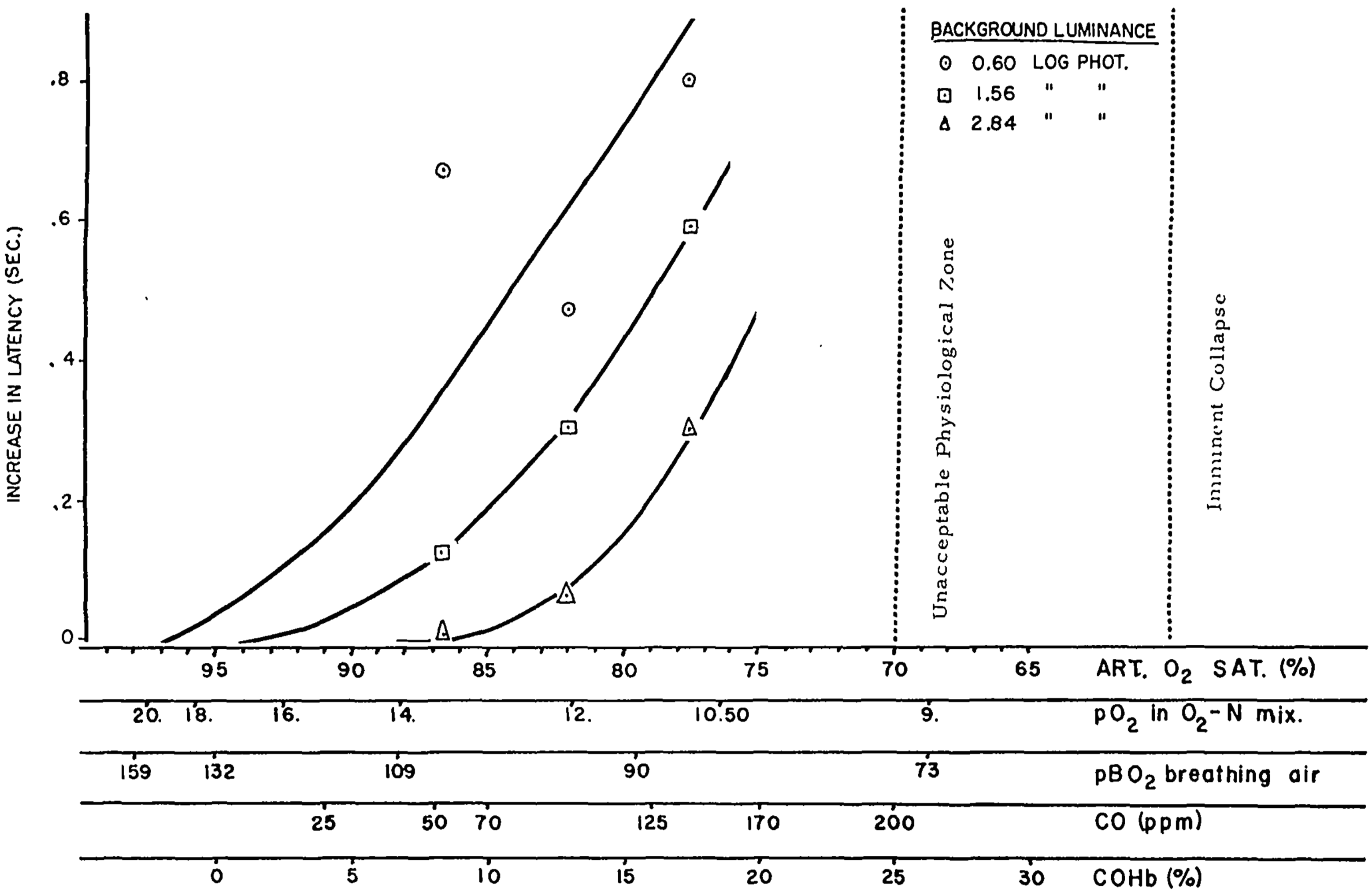

FIG. II-6 Latency of After-Image as a Function of Hypoxia. Data from McFarland et al., 1943.

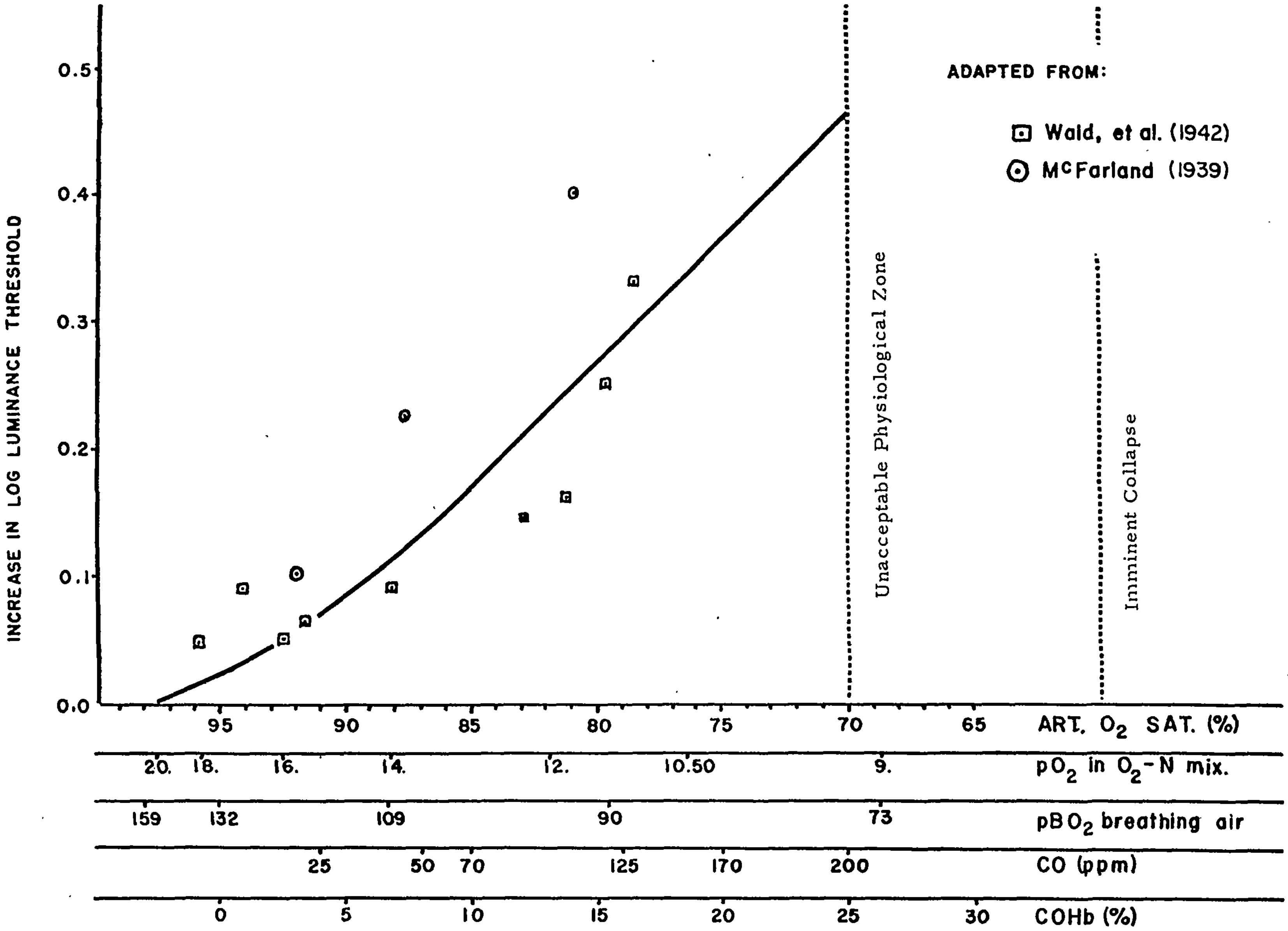

FIG. II-7 Effects of Hypoxia on Brightness Thresholds for Targets with Different Background Luminances

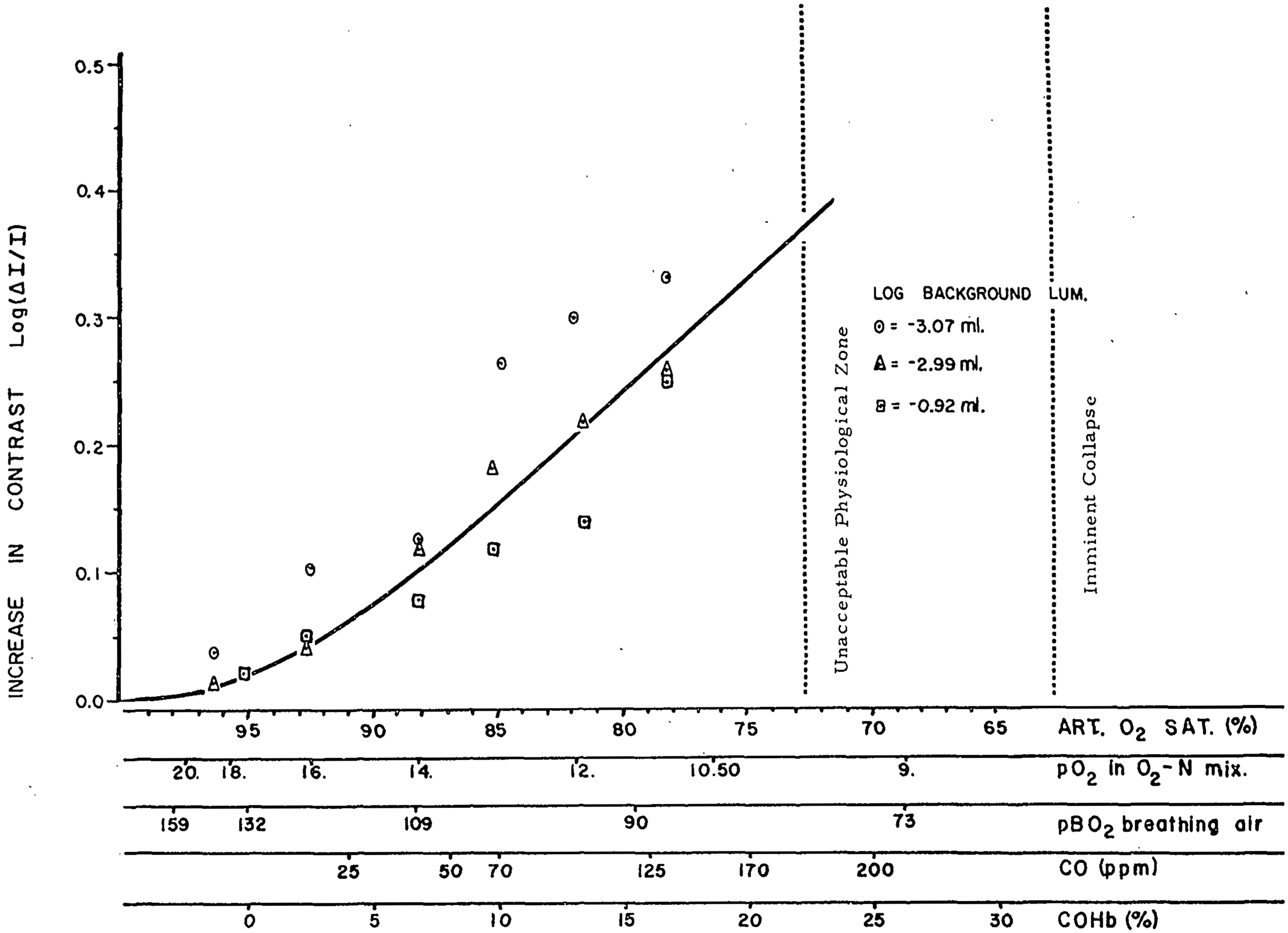

FIG. II-8 Effects of Hypoxia on Contrast Thresholds for Targets with Various Background Luminances. Based on Hecht et al, 1946.

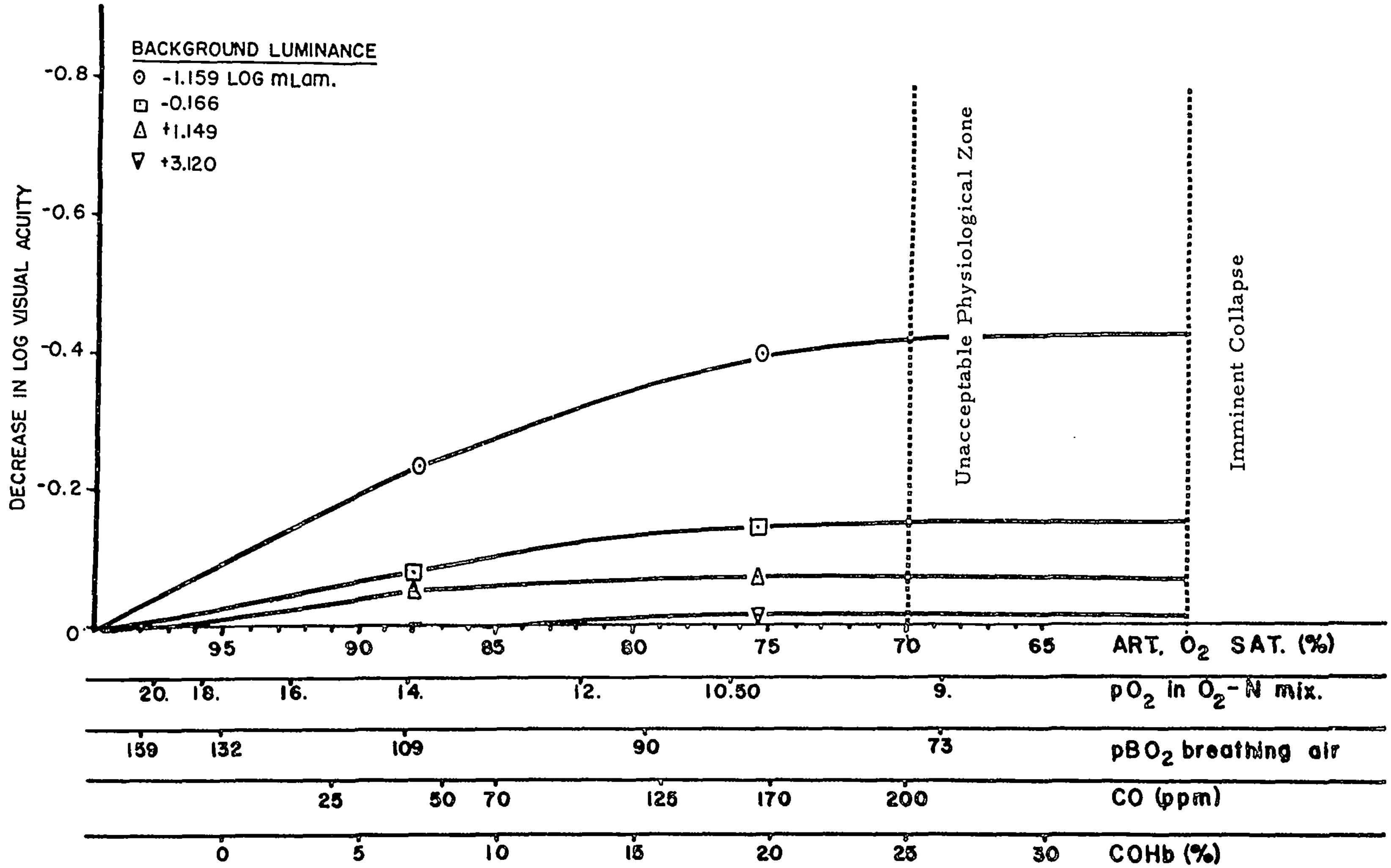

FIG. II-9 Effects of Hypoxia on Visual Acuity Thresholds for Targets with Different Background Luminances. Data from McFarland and Halperin, 1940.

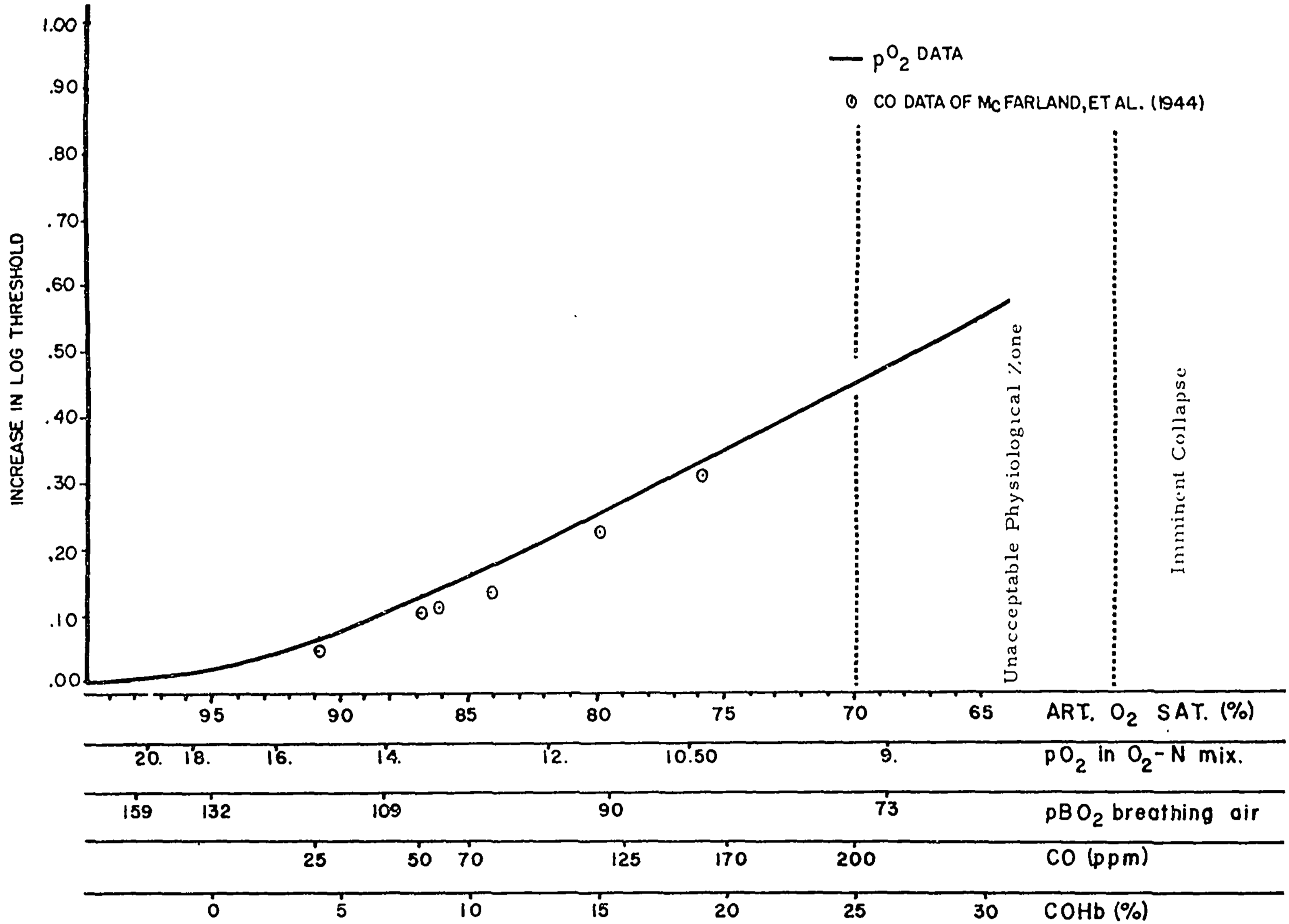

FIG. II-10 A Comparison of the Effects of CO and Reduced pO_2 on Brightness Threshold.

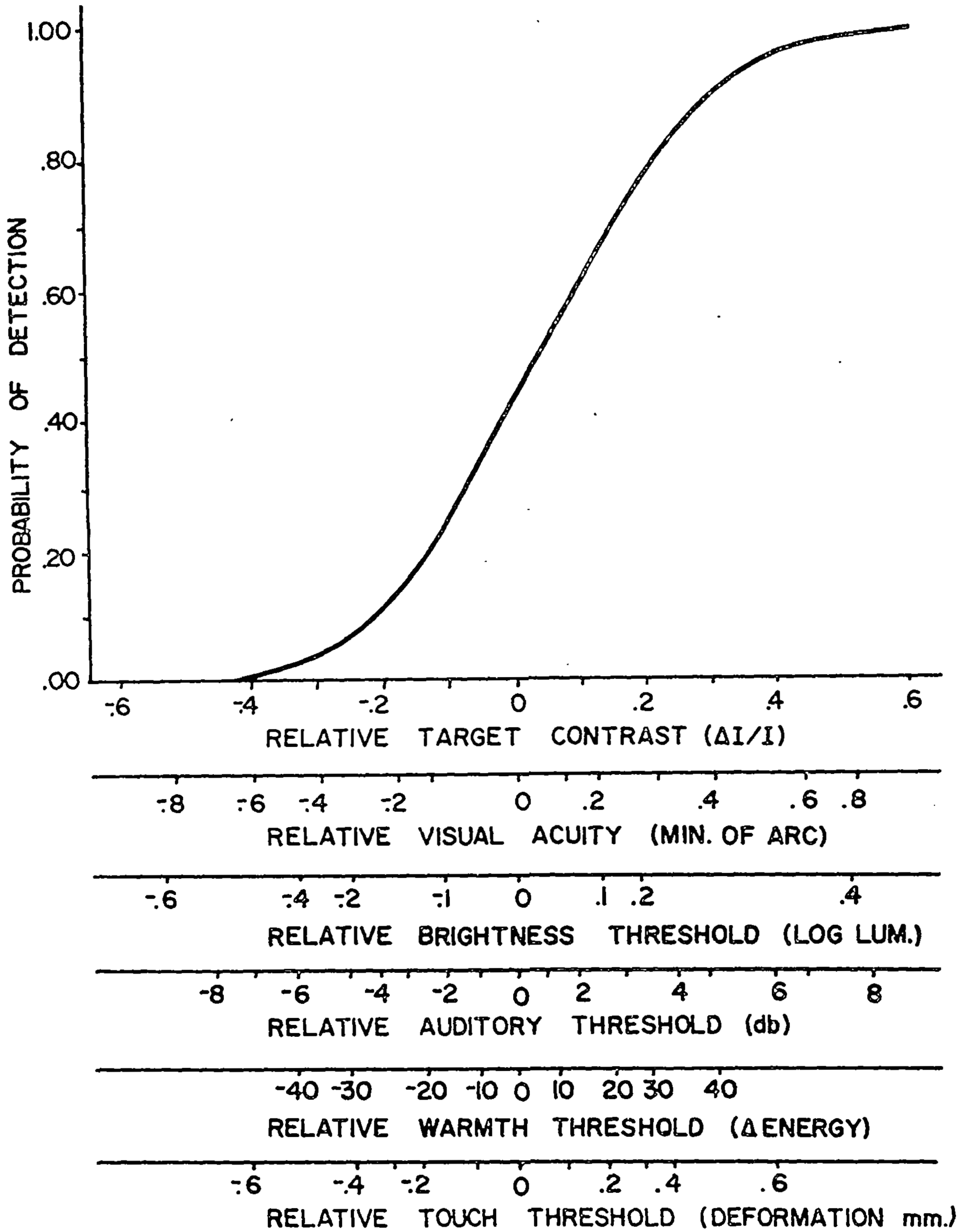

FIG. II-11 Probability of Detection as a Function of Deviation from the Normal, or 50% Threshold Value, for Various Psychophysical Measures.

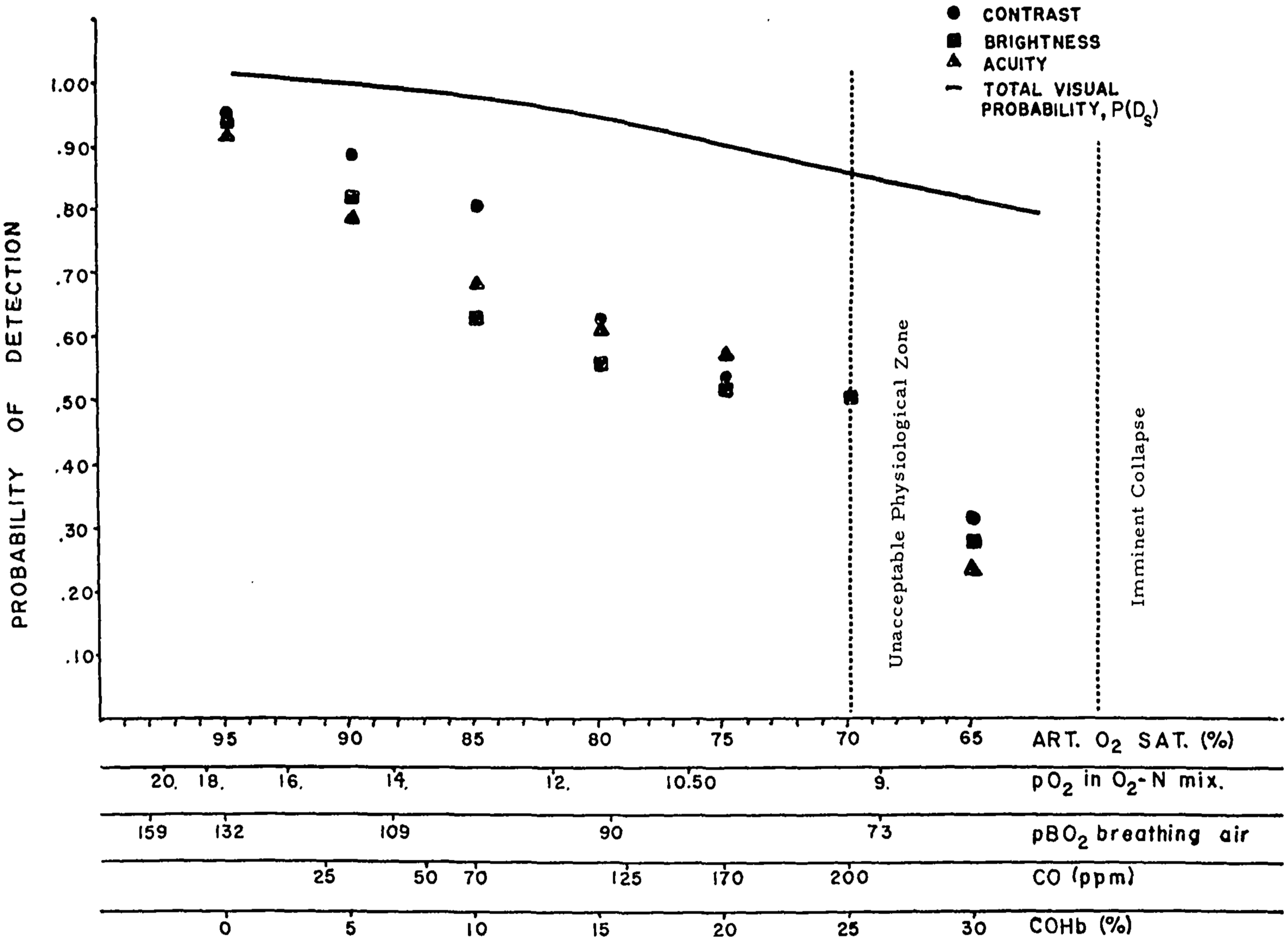

FIG. II-12 Derived Probability of Detection of a Target which is Normally Detected on the Basis of One Cue 98% of the Time, as a Function of Hypoxic Levels.

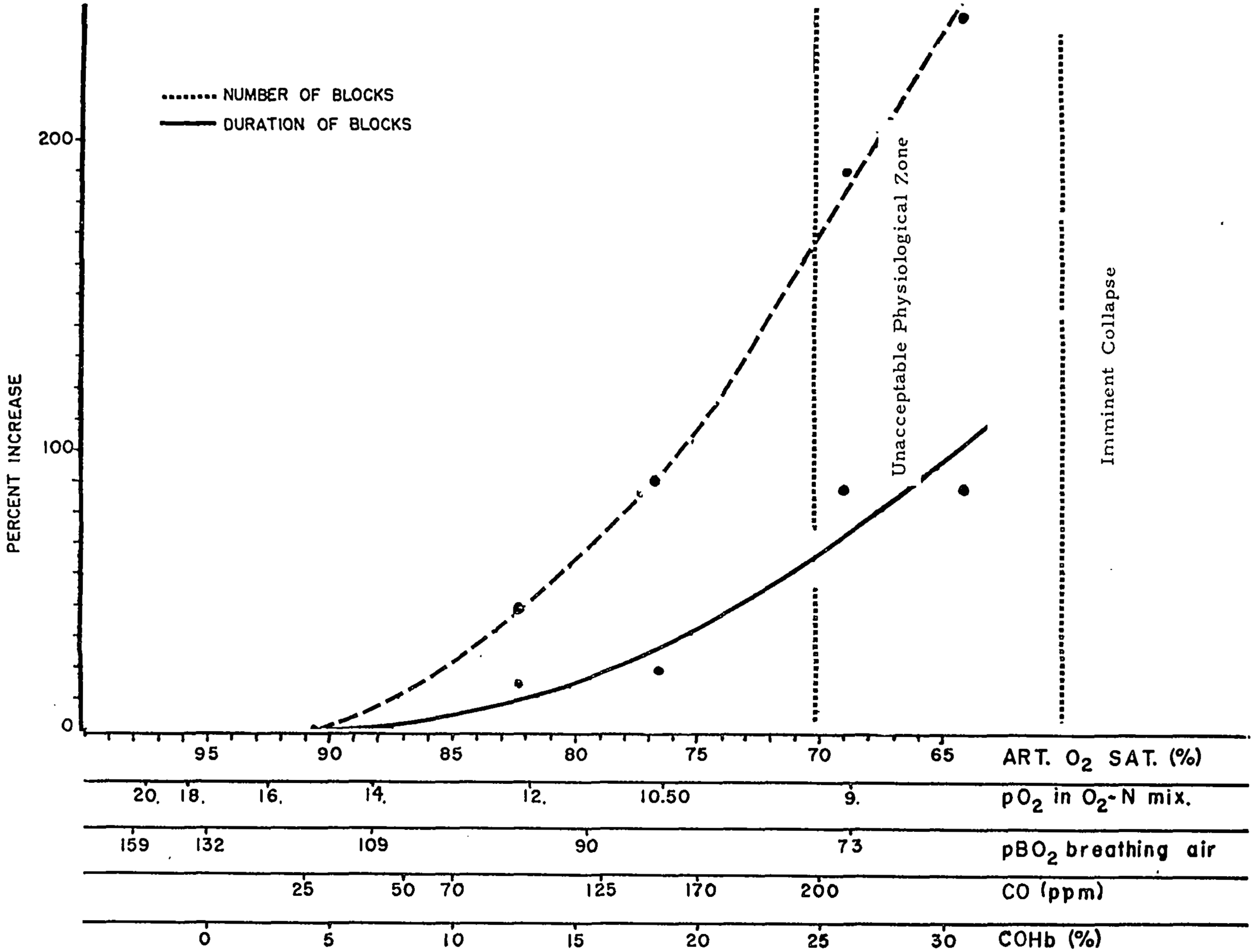

FIG. II-13 Expected Effects of Hypoxia on Response Blocking. Data from Bills, 1937

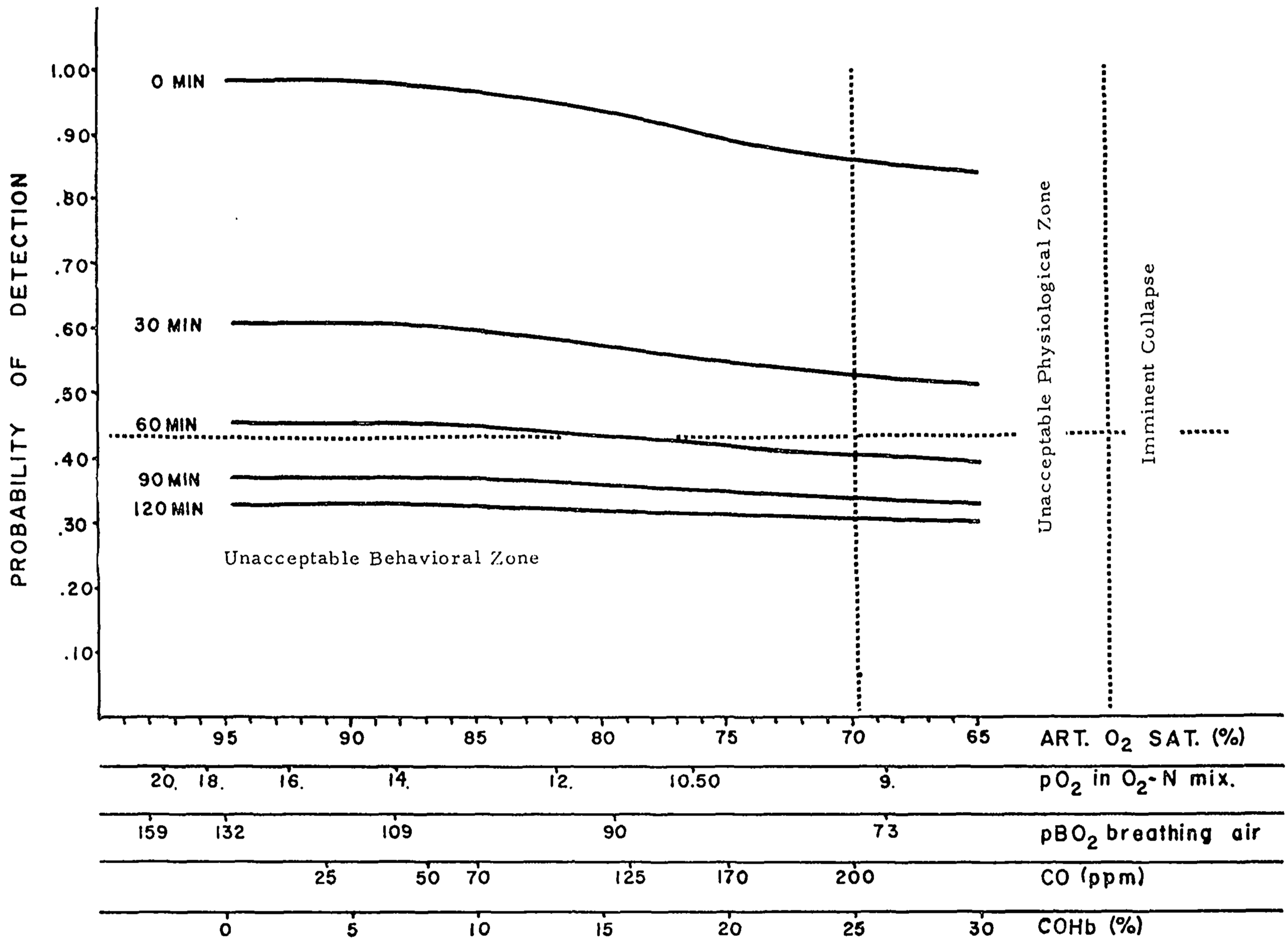

FIG. II-14 Predicted Search for one Possible Signal Arriving in a Known Position at an Unknown Time at Various Hypoxic Levels.

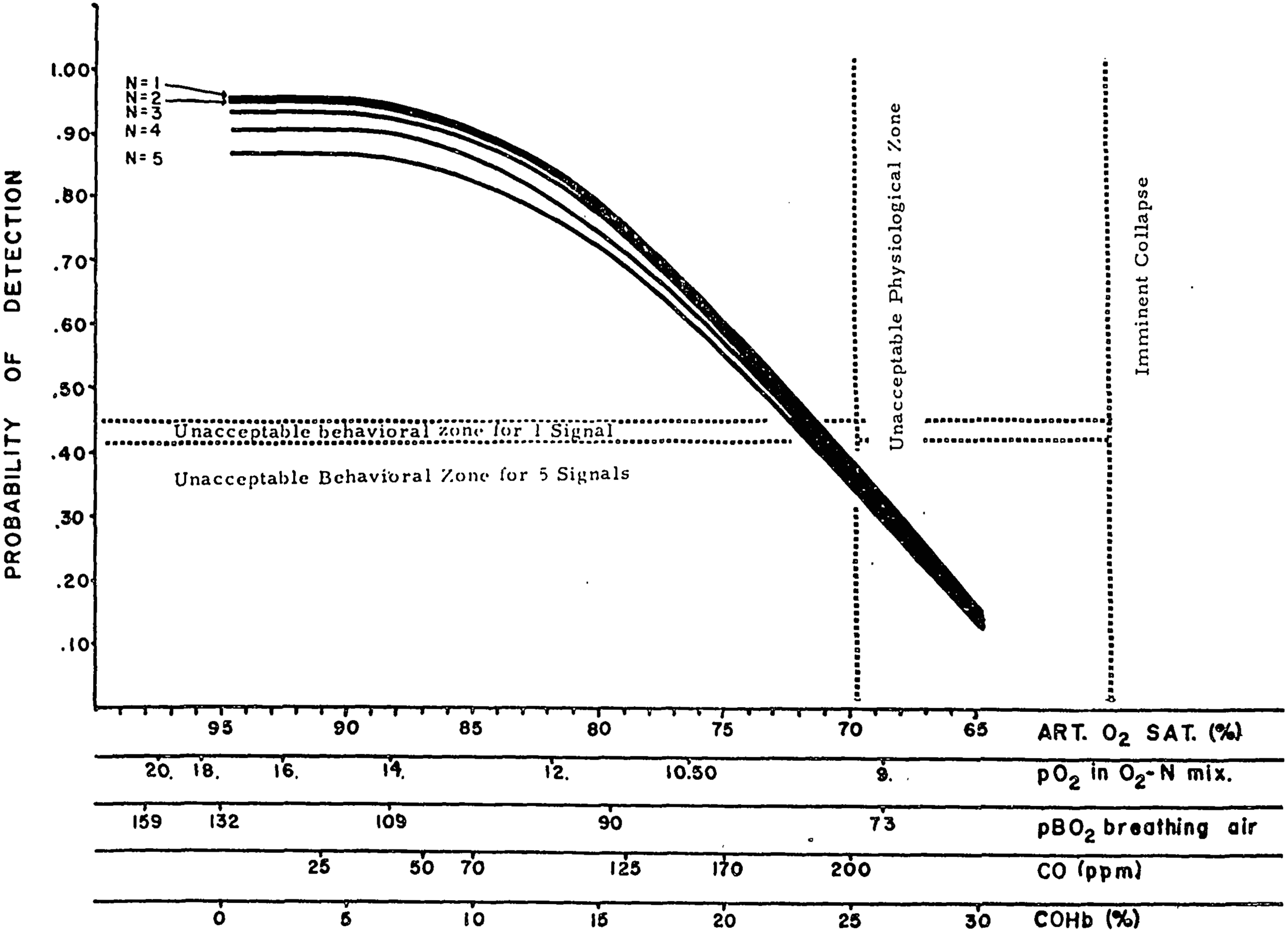

FIG. II-15 Predicted Search for One Signal of N Possible Signals as a Function of Hypoxic Levels the Signal Arriving at an Unknown Position and Time.

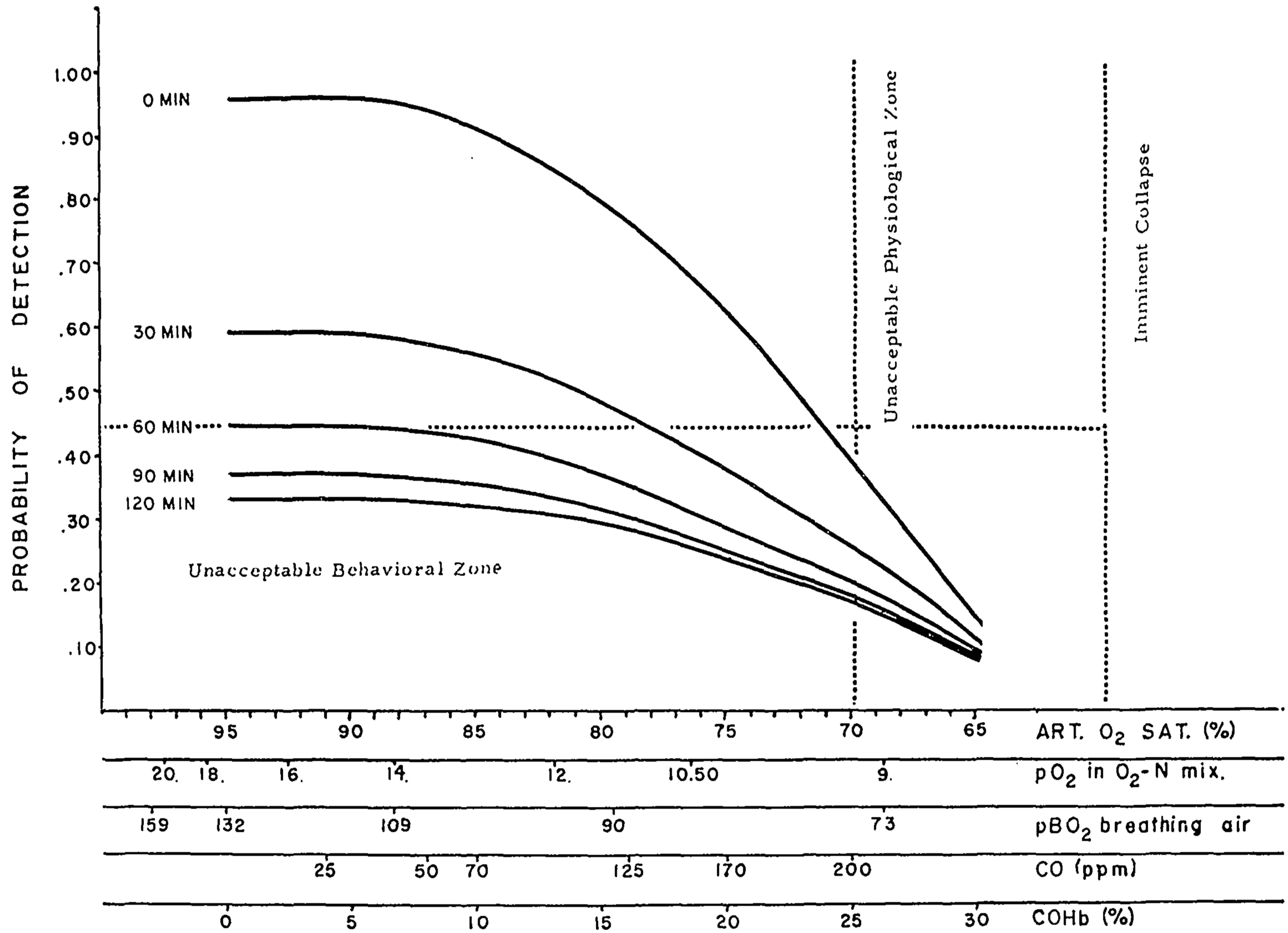

FIG. II-16 Predicted Search for One Possible Signal Arriving at an Unknown Position and Time as a Function of Hypoxic Levels and Time at Task.

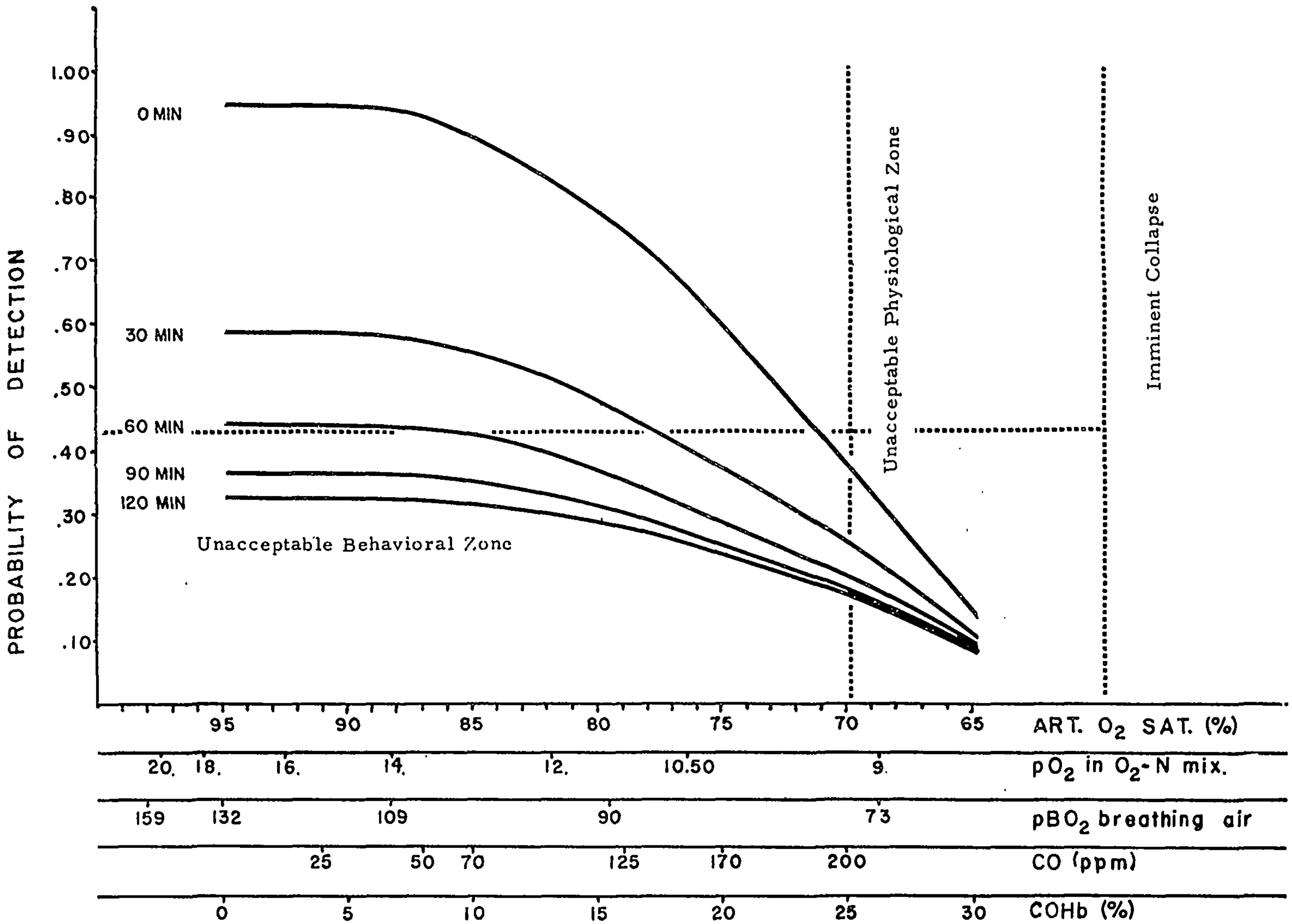

FIG. II-17 Predicted Search for One Signal of Two Possible Signals as a Function of Hypoxic Levels and Time at Task.

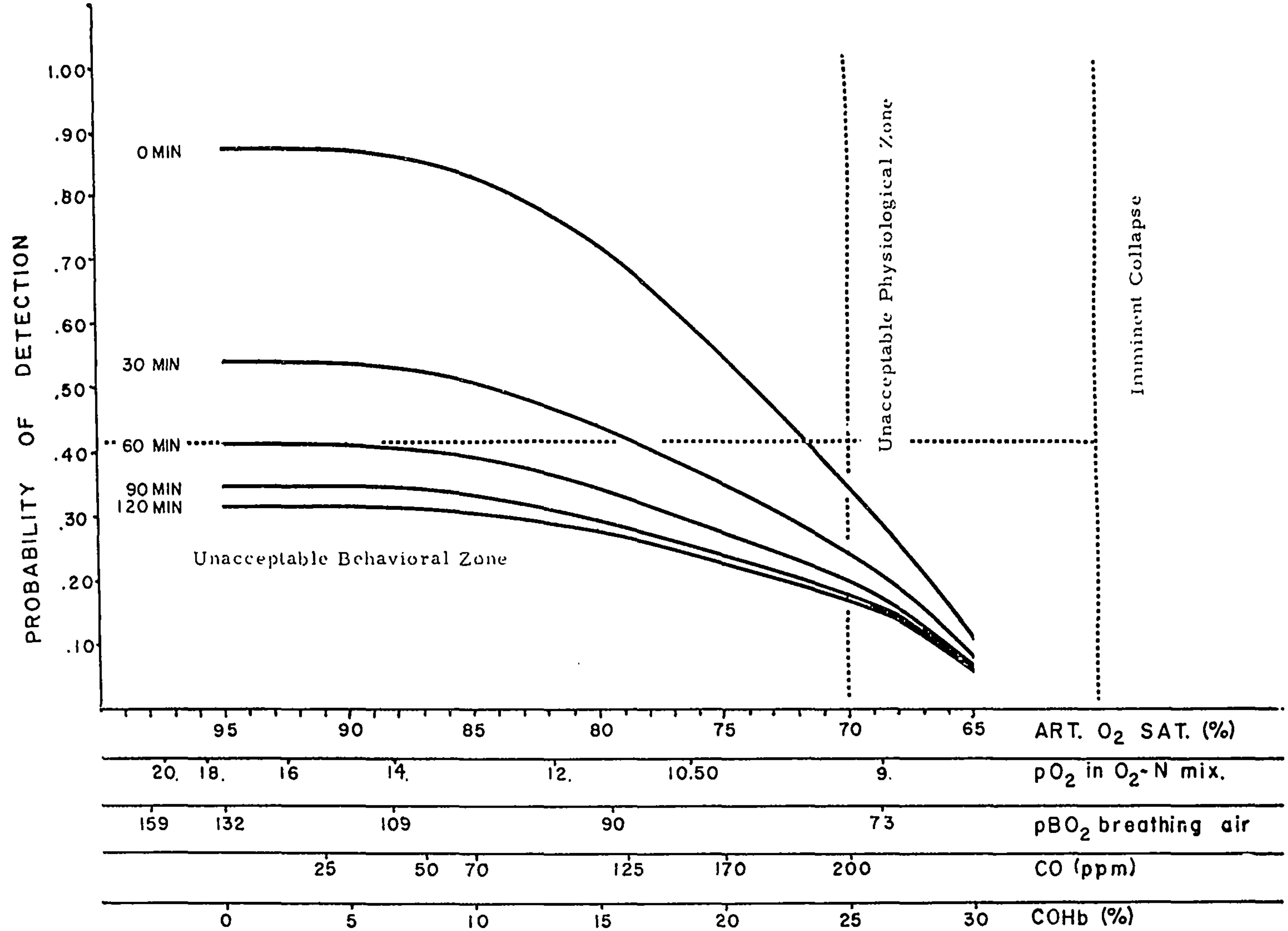

FIG. II-18 Predicted Search for One Signal of Five Possible Signals as a Function of Hypoxic Levels and Time at Task.

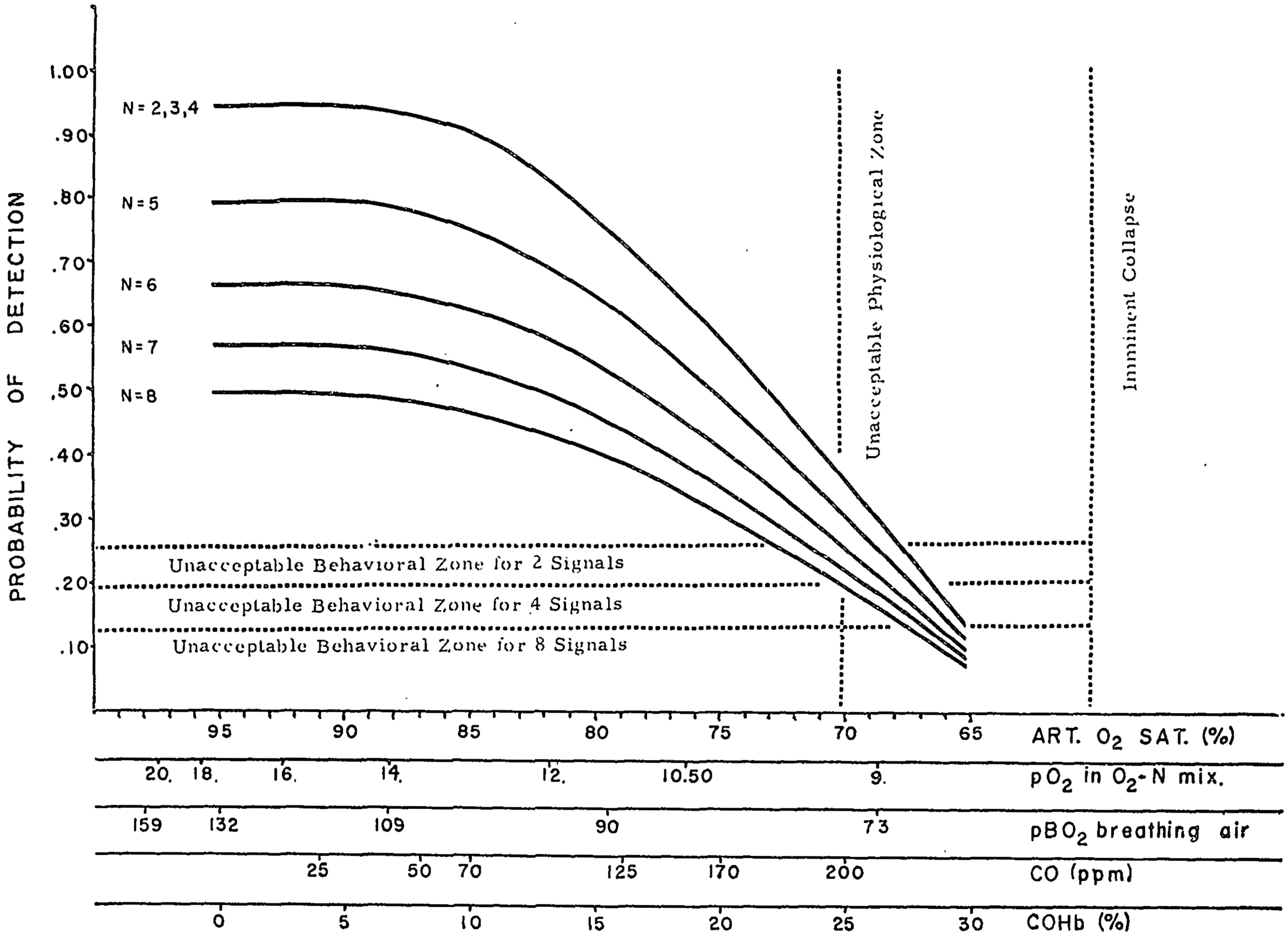

FIG. II-19 Predicted Search for N Simultaneously Presented Signals Arriving at an Unknown Position and Unknown Time.

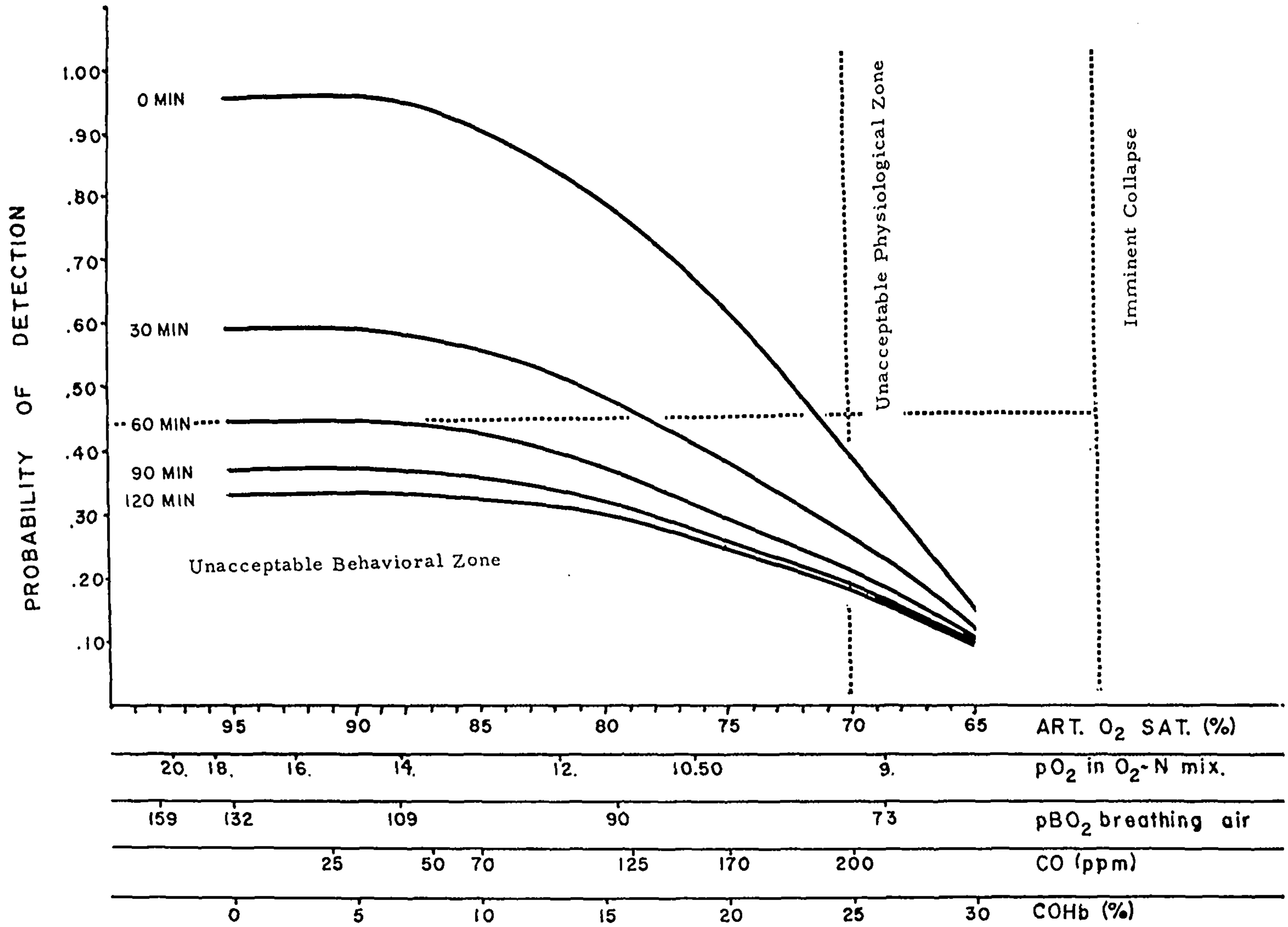

FIG. II-20 Predicted Search for 2, 3 or 4 Simultaneously Presented Signals as a Function of Hypoxic Levels and Time at Task.

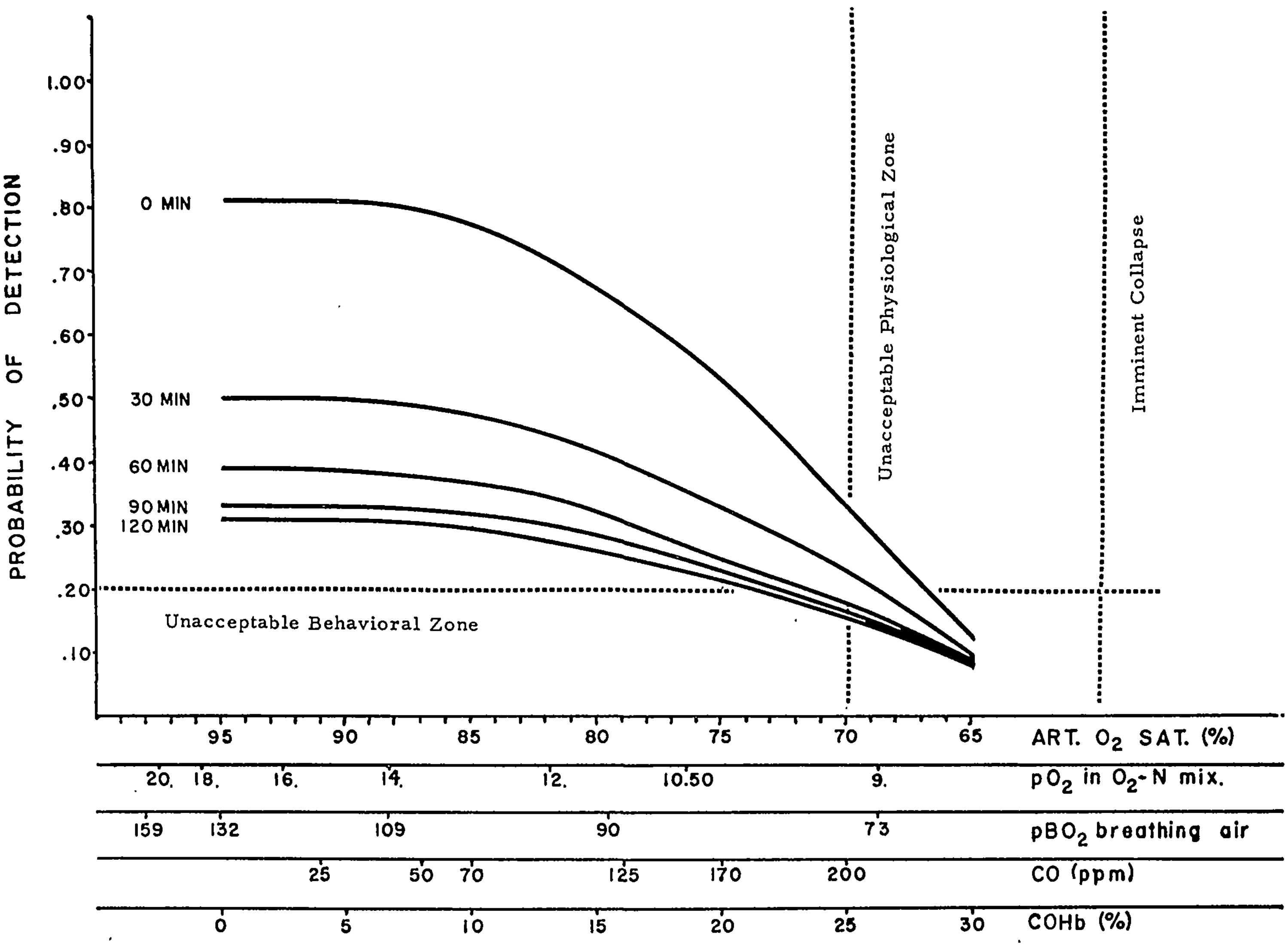

FIG. II-21 Predicted Search for Five Simultaneously Presented Signals as a Function of Hypoxic Level and Time at Task.

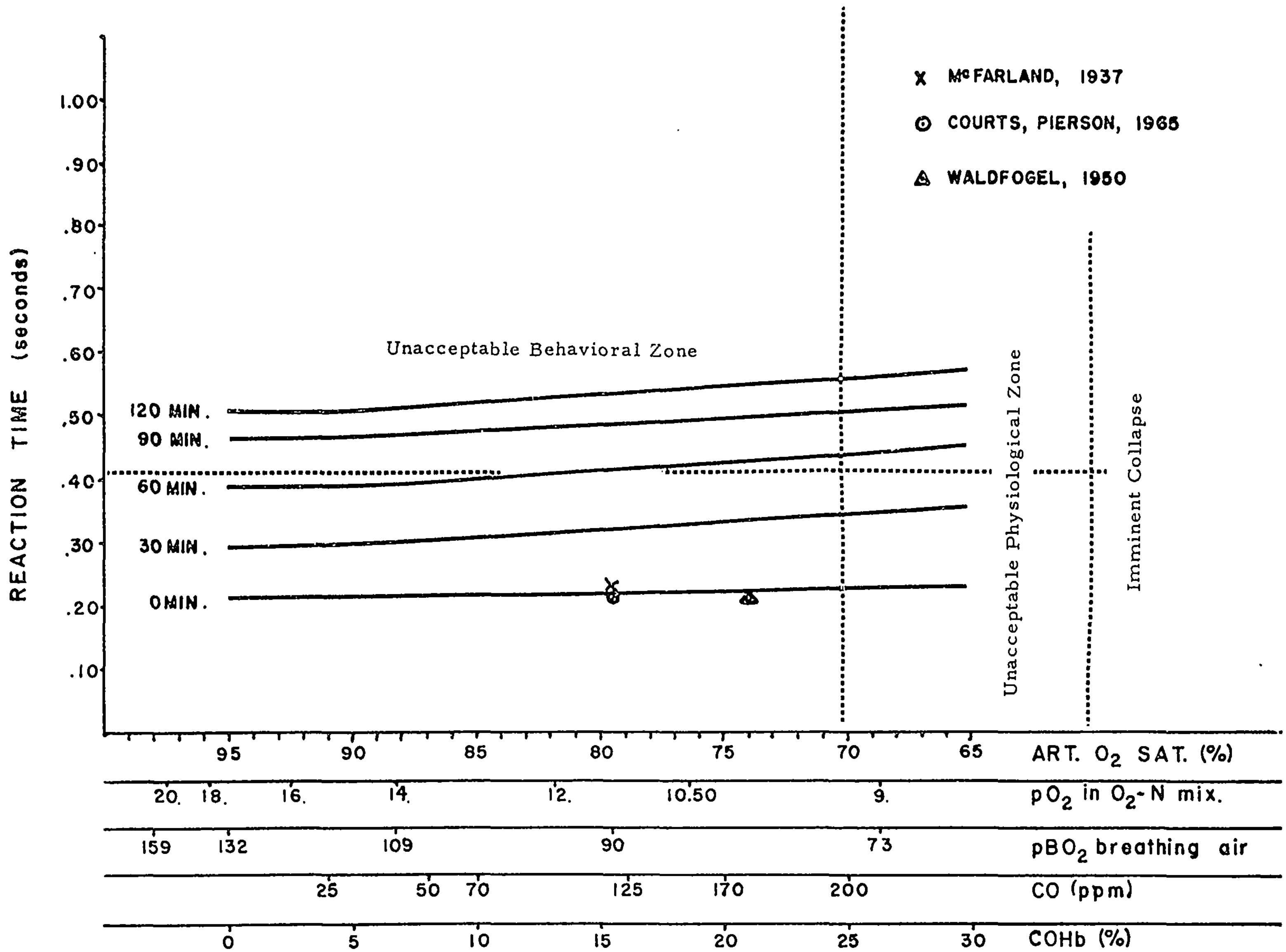

FIG. II-22 Predicted Switching Performance for One Possible Signal Arriving at a Known Position but at an Unknown Time as a Function of Hypoxic Level and Time at Task.

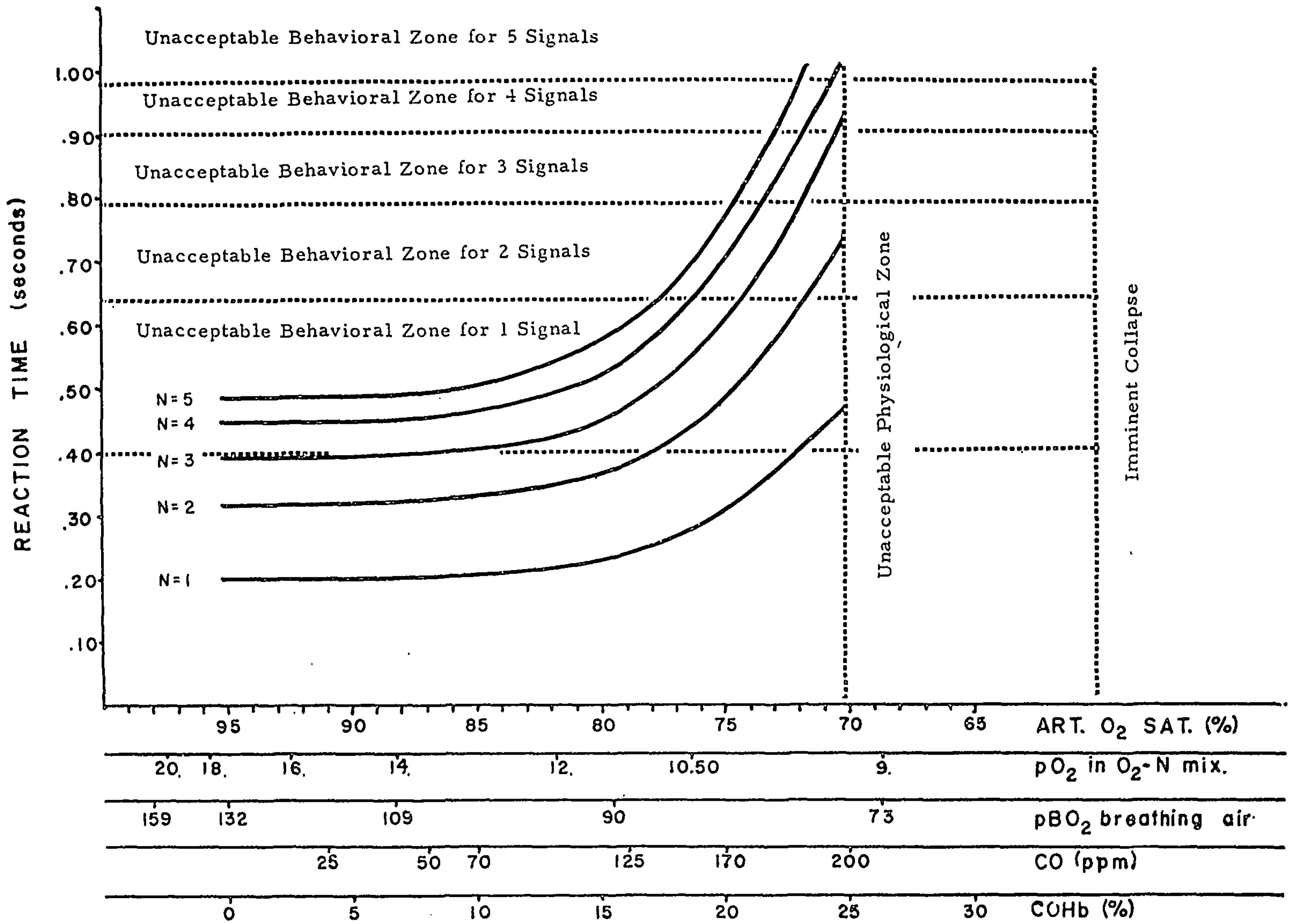

FIG. II-23 Predicted Switching Performance for One Signal of N Possible Signals as a Function of Hypoxic Level. The Signal Arrives at an Unknown Time and Position.

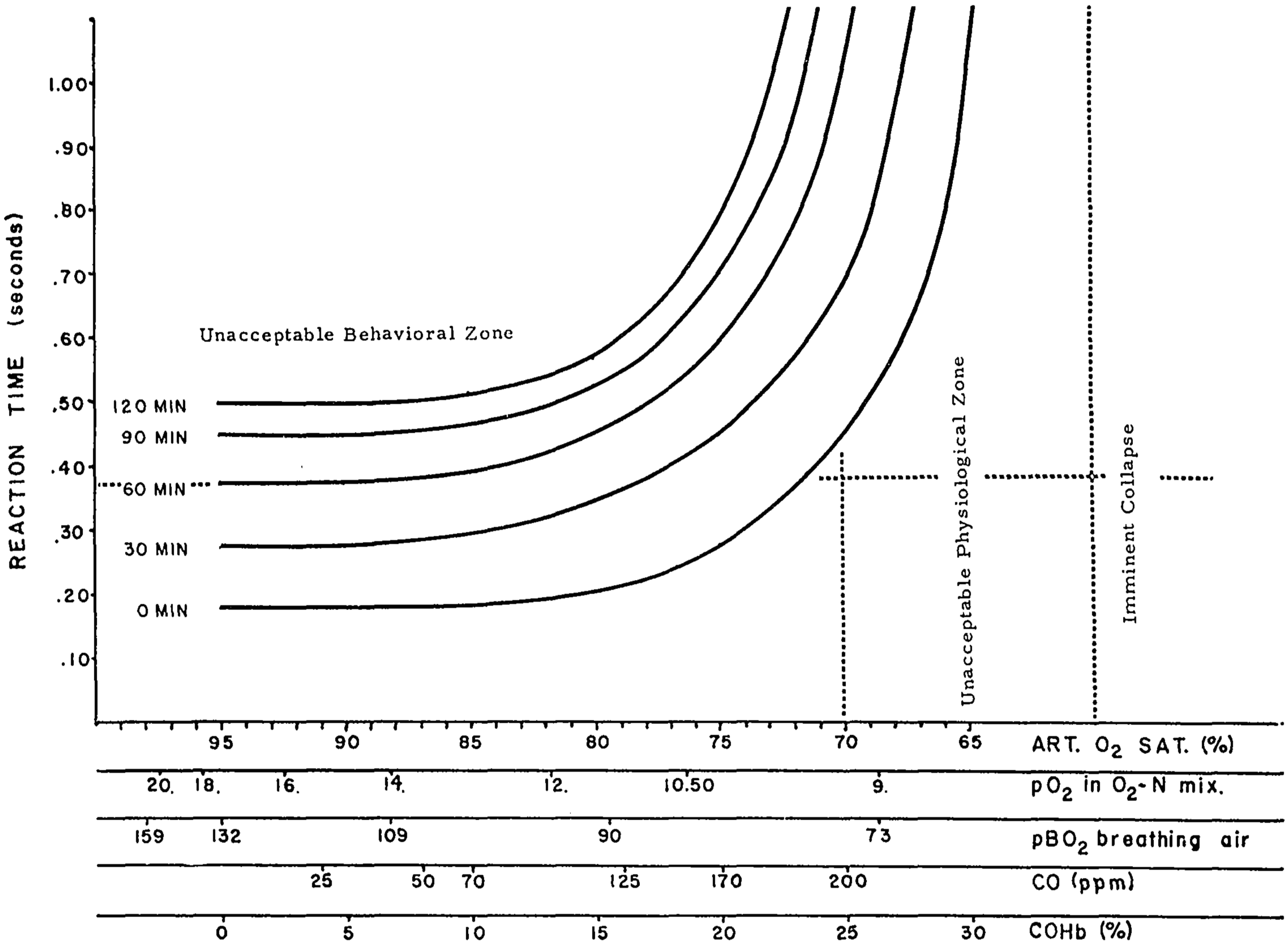

FIG. II-24 Predicted Switching Performance for One Possible Signal Arriving at an Unknown Time and Position as a Function of Hypoxic Level and Time at Task.

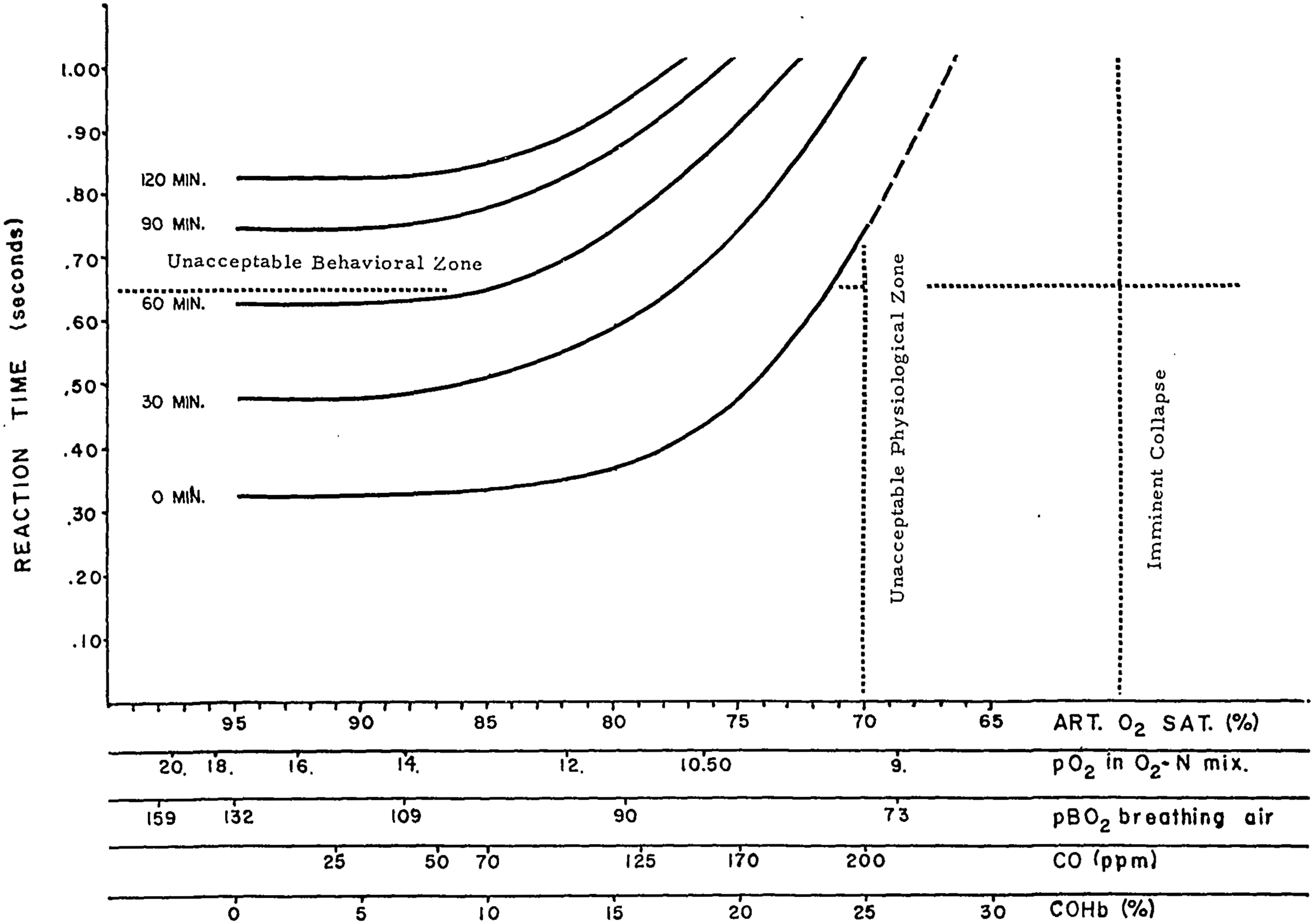

FIG. II-25 Predicted Switching for One Signal of Two Possible Signals as a Function of Hypoxic Level and Time at Task.

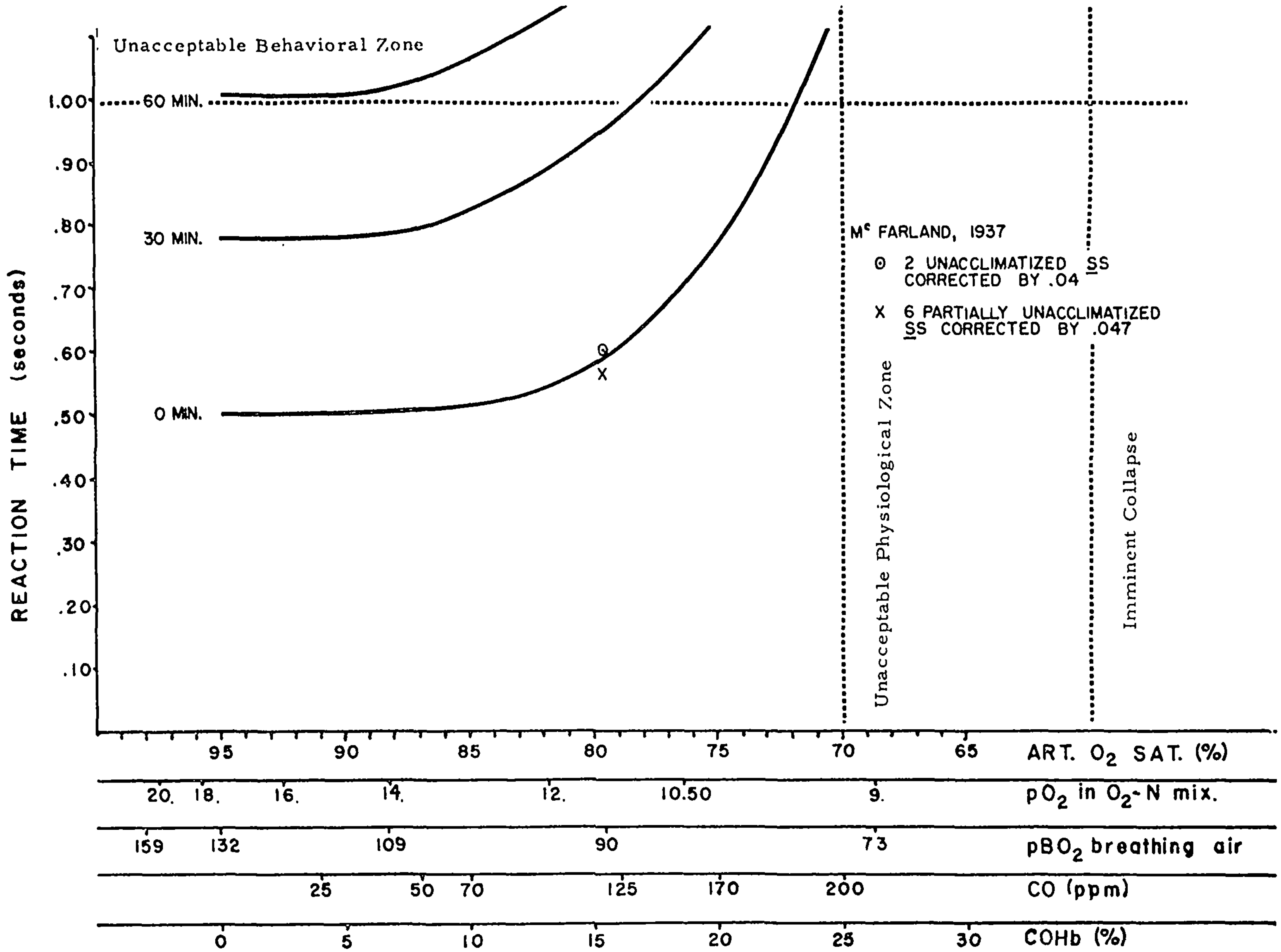

FIG. II-26 Predicted Switching for One Signal of Five Possible Signals as a Function of Hypoxic Level and Time at Task.

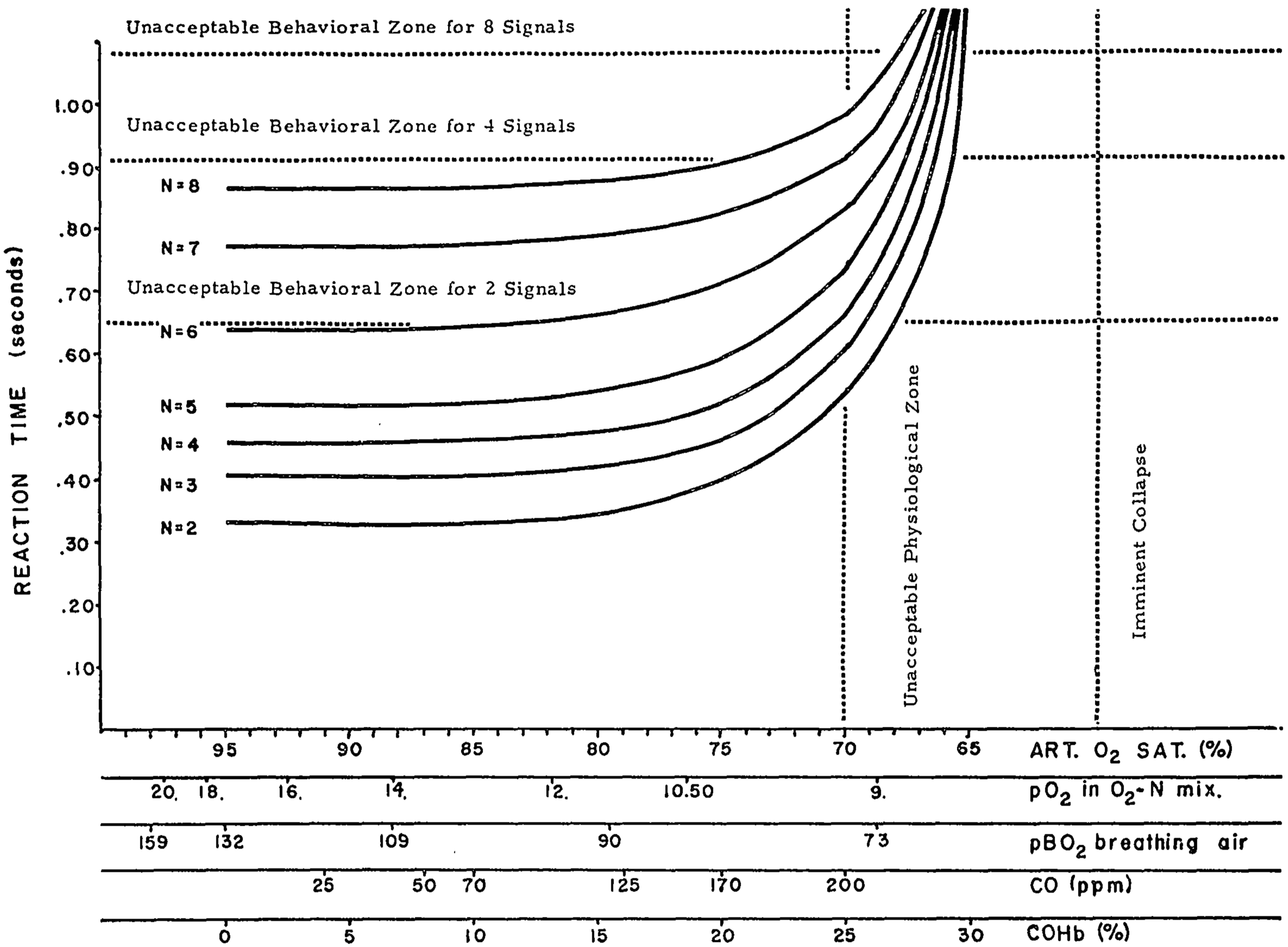

FIG. II-27 Predicted Switching for N Simultaneously Presented Signals as a Function of Hypoxic Level and Time at Task.

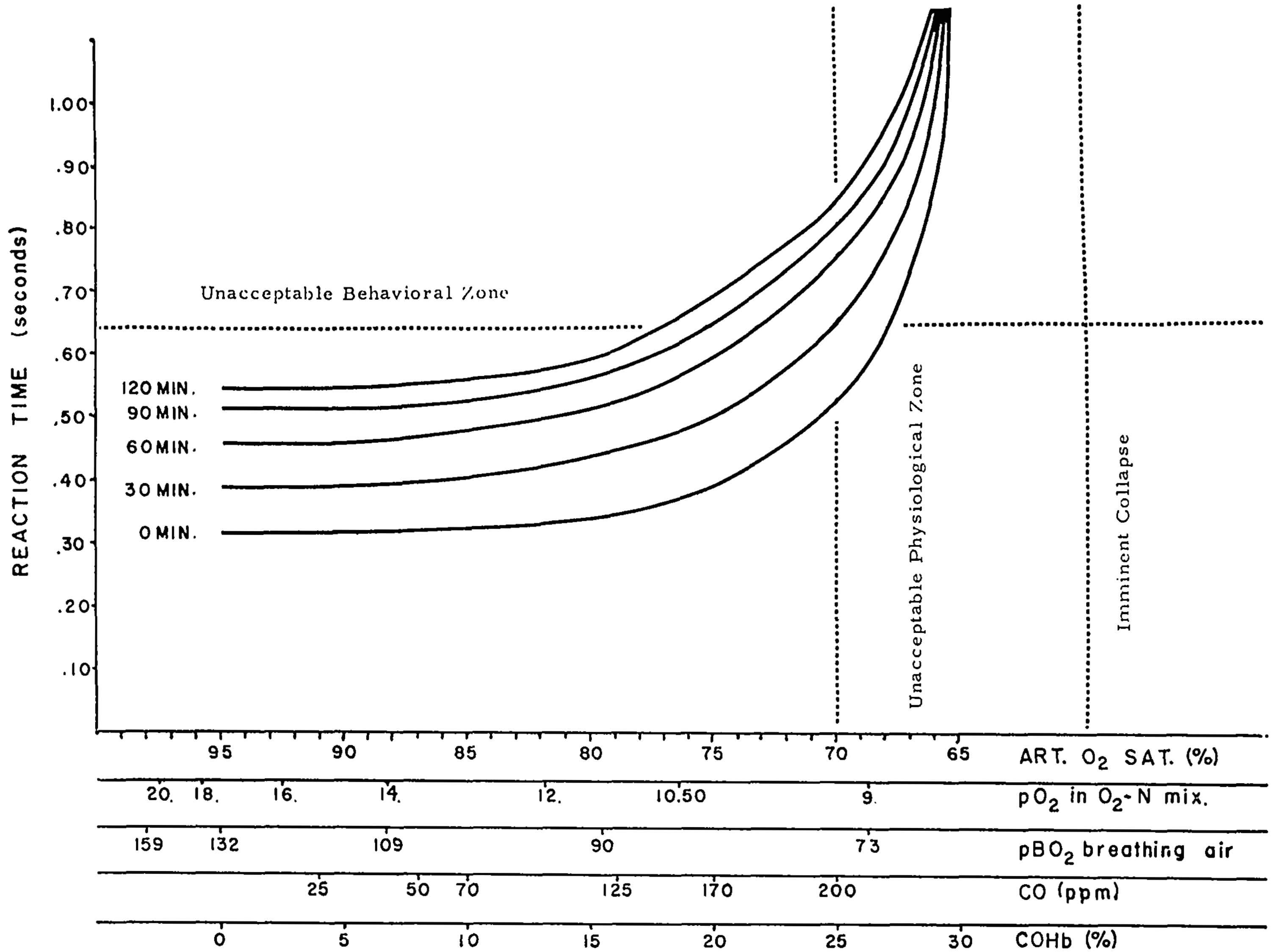

FIG. II-28 Predicted Switching for Two Simultaneously Presented Signals as a Function of Hypoxic Level and Time at Task.

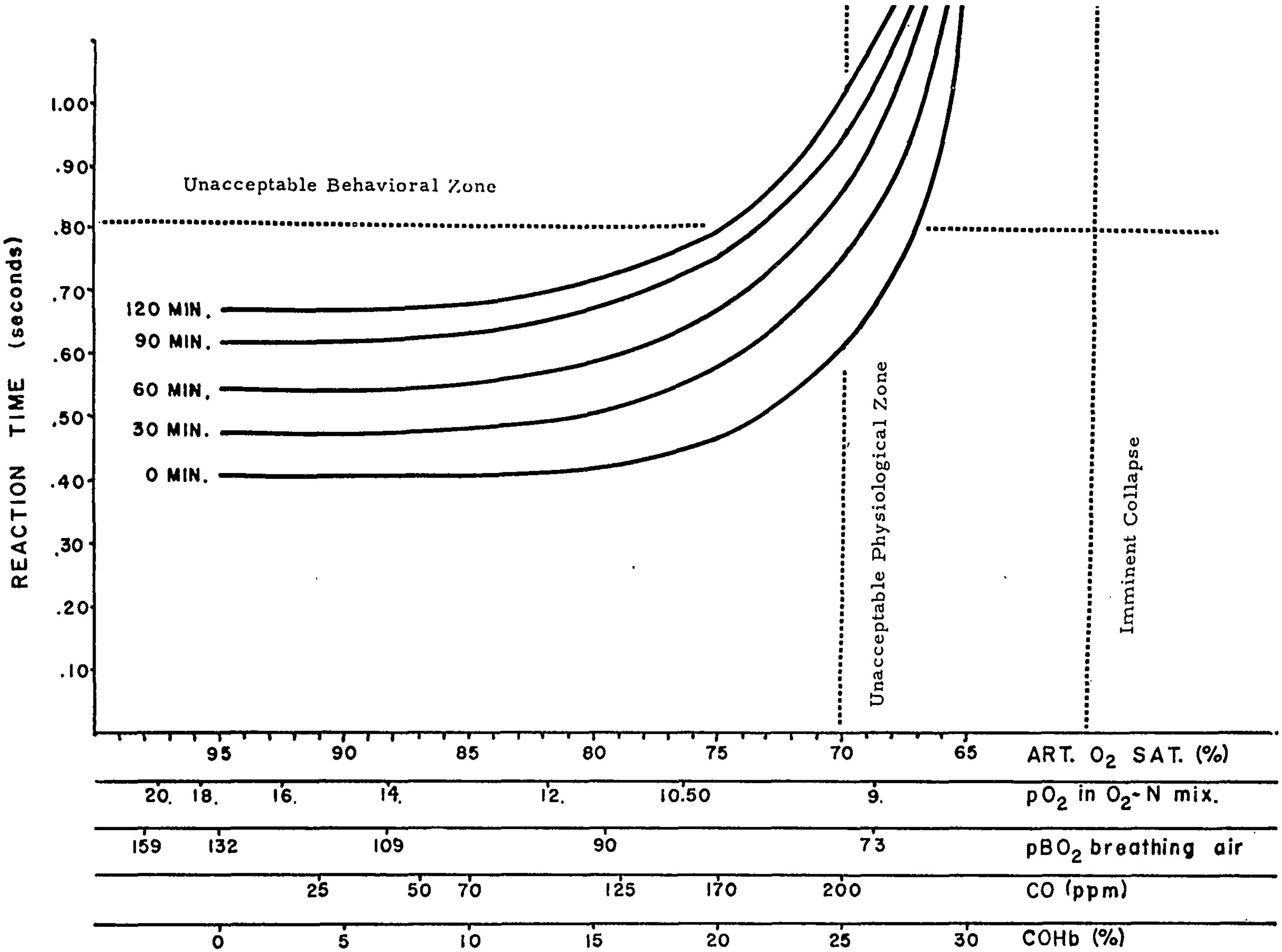

FIG. II-29 Predicted Switching for Three Simultaneously Presented Signals as a Function of Hypoxic Level and Time at Task.

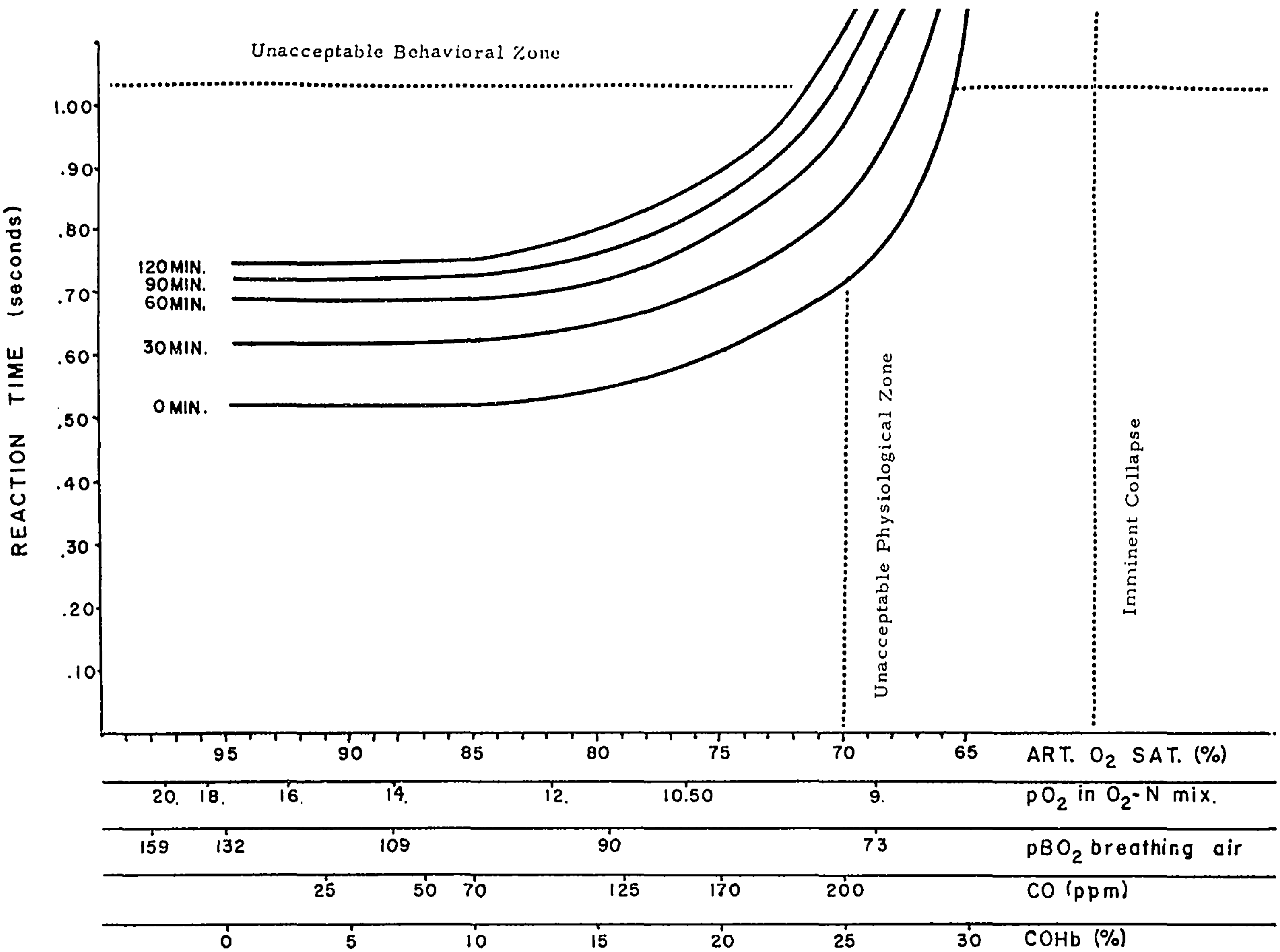

FIG. II-30 Predicted Switching for Five Simultaneously Presented Signals as a Function of Hypoxic Level and Time at Task.

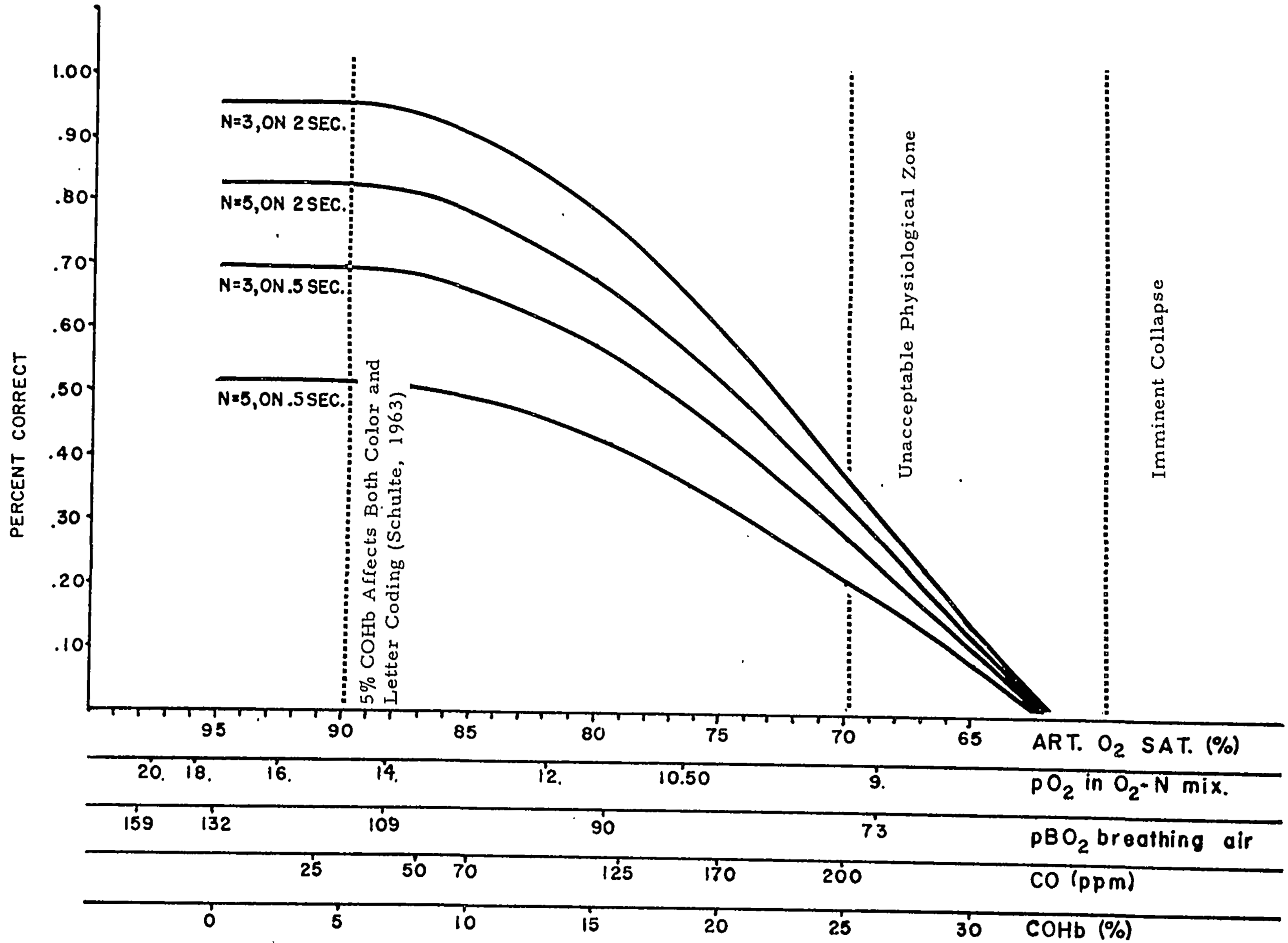

FIG. II-31 Predicted Coding of 3 Signals and 5 Signals as a Function of Hypoxic Levels for Signal Durations of .5 Second and 2 Seconds.

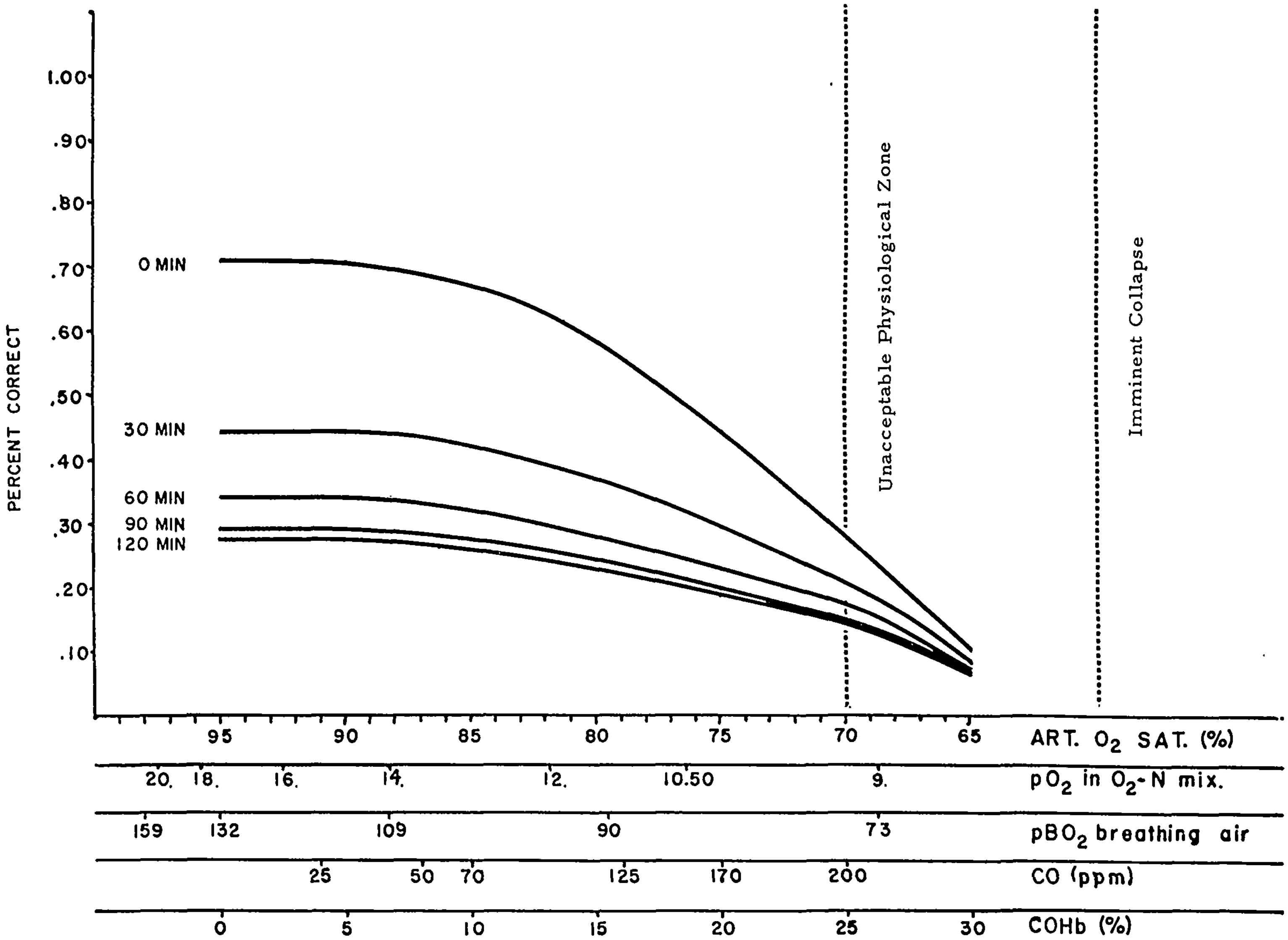

FIG. II-32 Predicted Coding Performance as a Function of Hypoxic Levels and Time at Task for Three Simultaneous Signals Presented for .5 Second Duration.

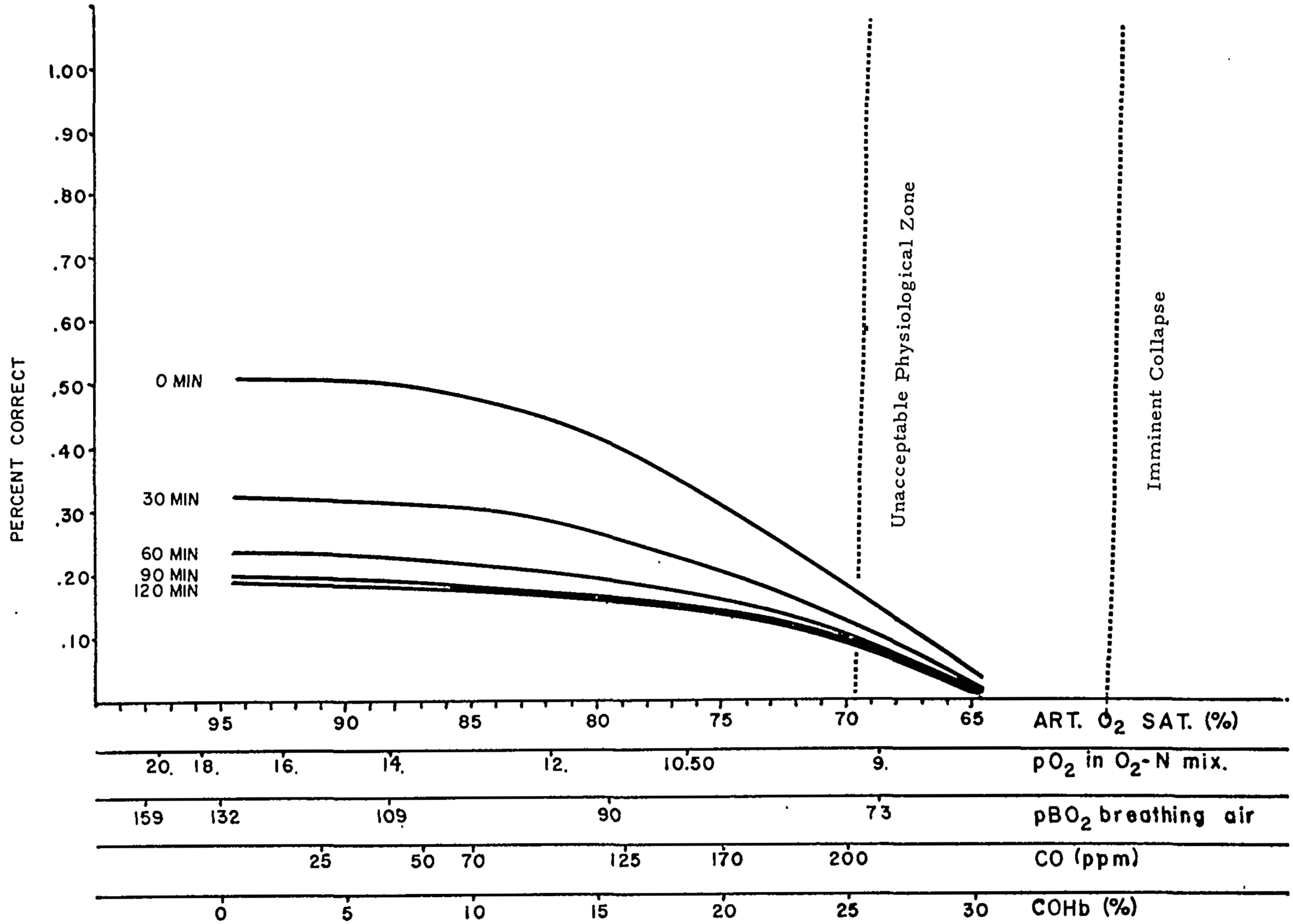

FIG. II-33 Predicted Coding Performance as a Function of Hypoxic Levels and Time at Task for Five Simultaneous Signals Presented for .5 Second Duration.

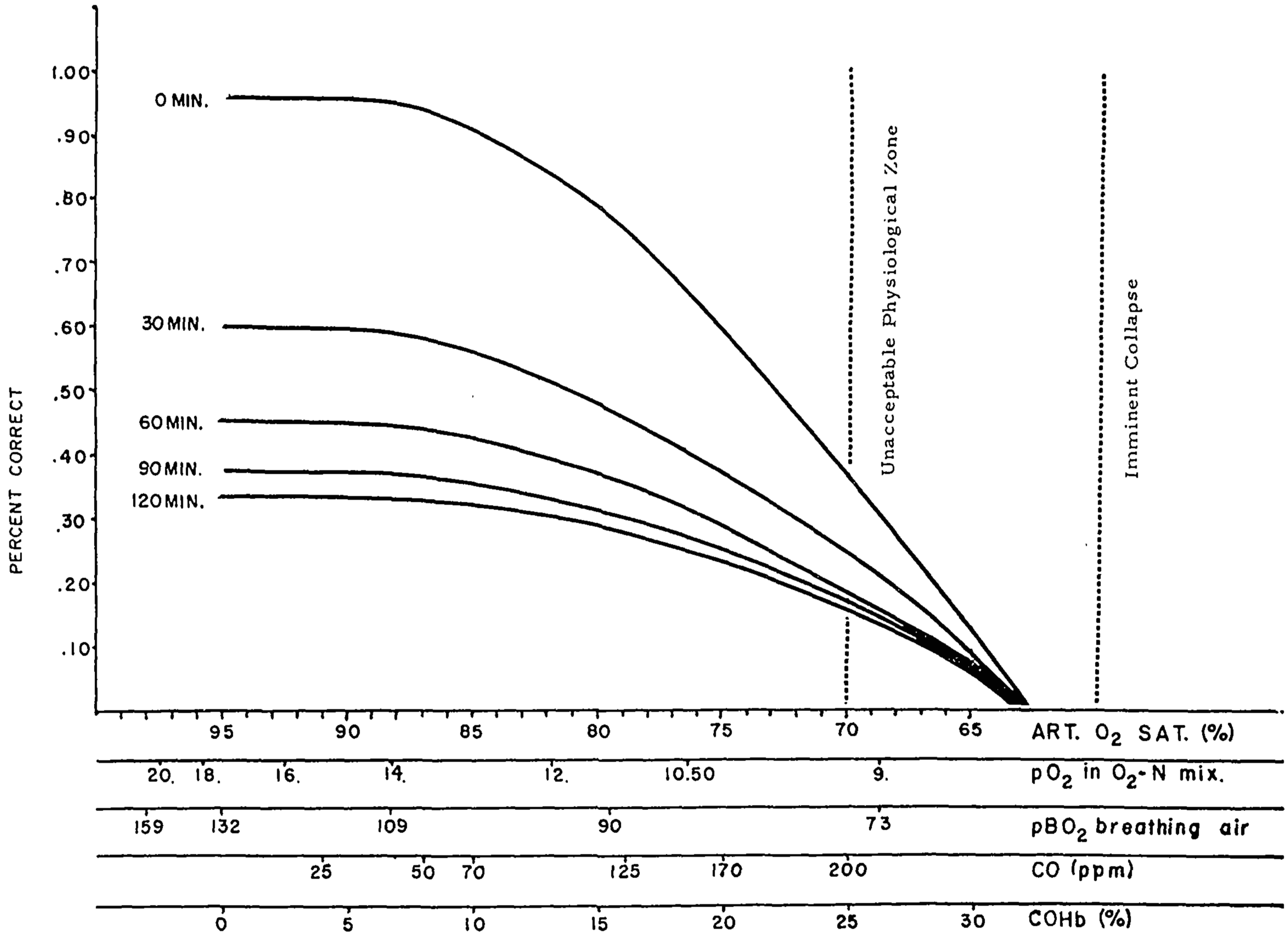

FIG. II-34 Predicted Coding of 3 Signals Presented for 2 Seconds as a Function of Hypoxic Levels and Time at Task.

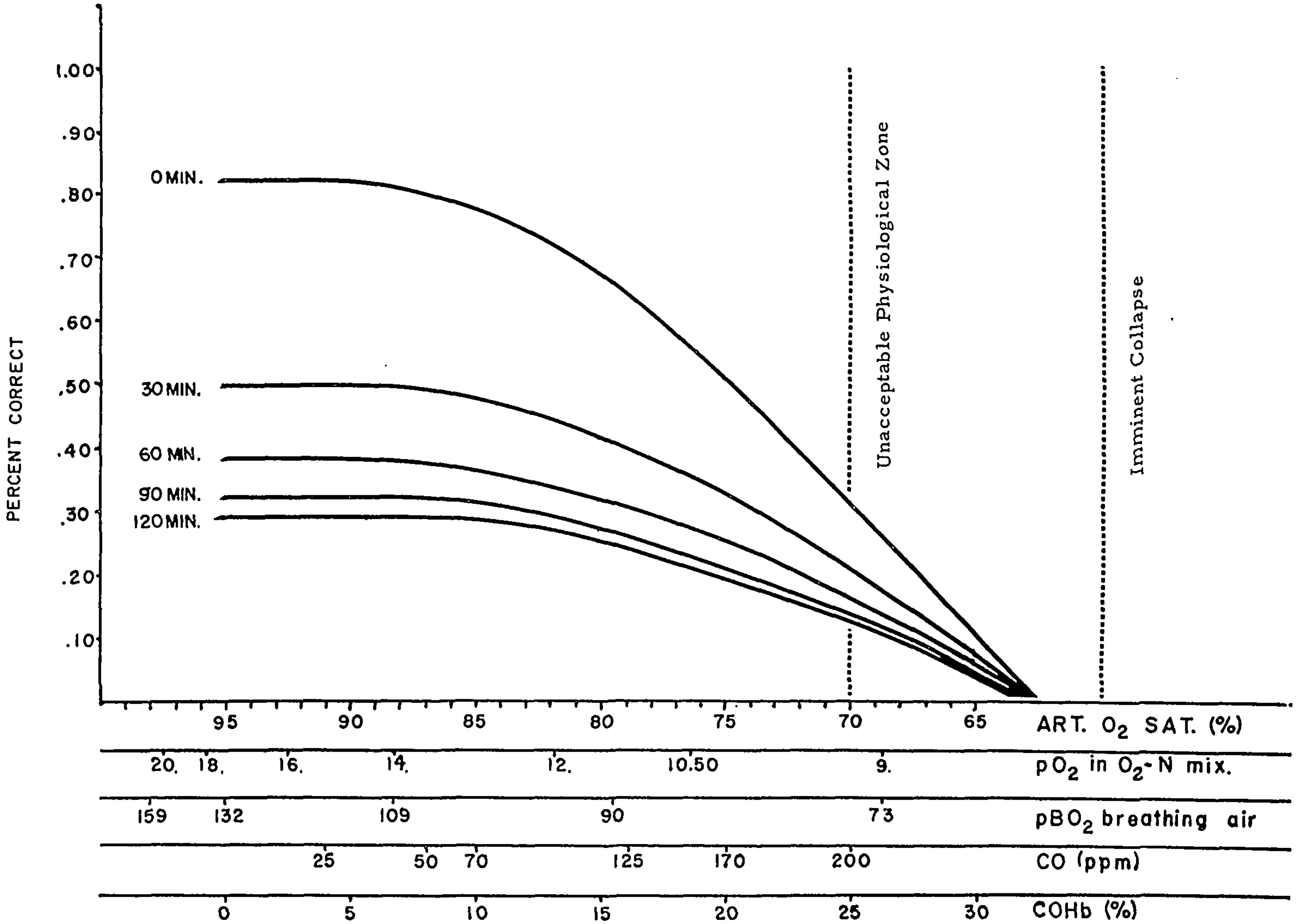

FIG. II-35 Predicted Coding of 5 Signals Presented for 3 Seconds as a Function of Hypoxic Levels and Time at Task.

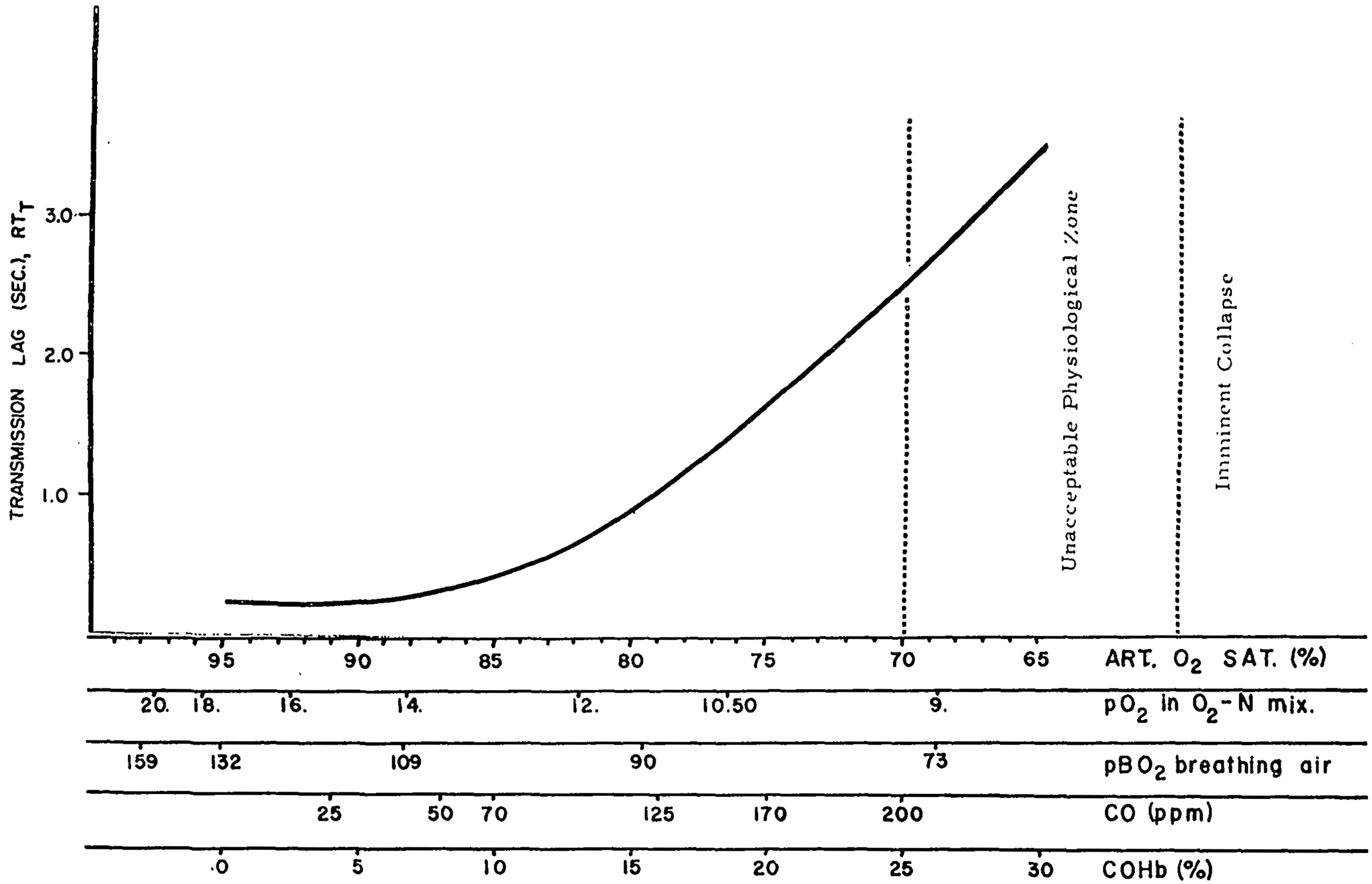

FIG. II-36 Predicted Relationship Between Human Transmission Lag, RT_T, and Hypoxia

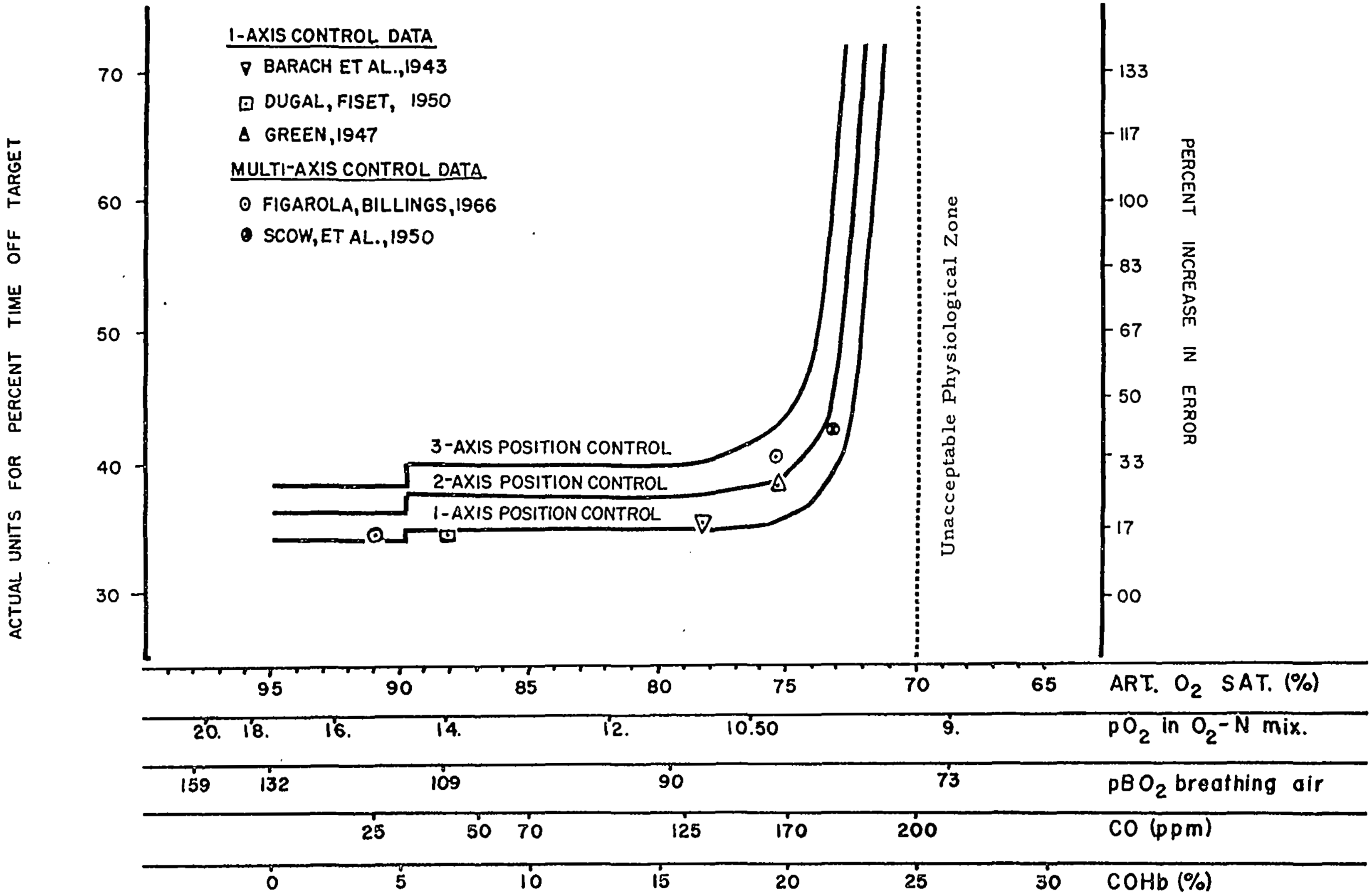

FIG. II-37 Predicted Tracking Performance as a Function of Hypoxia. 30% Time-off-target has been Assumed as Normal, or 0% Increase in Error, in Order to Compare Data

Predicting Human Performance in Space Environments

III. The Mechanical Environment: Positive Transverse Acceleration (+Gx)

From the possible mechanical environmental forces we have selected positive transverse acceleration (+Gx) as a problem area of special interest to space missions. This selection has the additional value of evaluating our ability to generalize across environments which have some, but not all of the same major physiological effects.

Physiological tolerance to linear acceleration depends upon: the direction of the acceleration, the rate of increase or decrease in acceleration, peak time, magnitude, and duration of exposure. A thorough discussion of these factors may be found in many sources, i.e., see Compendium of Human Responses to the Aerospace Environment. Environmental conditions such as the atmospheric pressure, partial pressure of inspired oxygen, and the restraining system will also affect tolerance. In this discussion, however, we shall assume a +Gx of 120 seconds exposure and ignore other factors except the atmospheric pressure and the nature of the inspired air. By +Gx we refer to an accelerative force applied from the front to the back of the body. Such a force results when the motion of the body itself is in a forward direction. The limiting physiological effects of +Gx are the result of a ventilatory and perfusional failure at the blood-lung interface. Associated reductions of the arterial oxygen saturation at the retina and the brain appear to be the basis for tolerance limits, and for performance effects other than those which result strictly from an inability to move limbs against the force. Performance effects due to actual movement impairment cannot be predicted for all controls as the actual performance also depends upon such factors as the force required by the control, the allowable error of control, etc. As before, it is necessary to determine these effects within the context of the specific task and add decrements to those to be predicted below.

I. Physiological and Sensory Effects

A. Physiological Equivalences

Figure III-1 presents the effects of +Gx on the arterial oxygen saturation. The data are from several studies each using subjects breathing air, at normal atmospheric pressure, exposed for 120 seconds and restrained. Figure III-2 is comparable except that subjects are breathing 100 percent oxygen at 5 psia. All figures to be presented below are drawn using the mean or fitted lines of these figures as physiological equivalents of the acceleration environment. The physiological tolerance limits to be employed are arterial oxygen saturations (% Art. O_2) of 77 percent and 74.5 percent. Seventy-seven percent Art. O_2 represents the point at which subjects have been found unable to move their bodies except for their hand and wrist, while 74.5% Art. O_2 is the average point of voluntary tolerance. More extreme limits can be taken to be the same as those shown in Part II.

B. Sensory Effects of +Gx

Since +Gx affects arterial oxygen content, it is to be expected that an increasing visual decrement will be found at increasing magnitudes of acceleration. Figure III-3 confirms this expectation for binocular visual acuity as a function of +Gx and associated arterial O_2 levels (White and Jorve, 1956). Figure III-4 shows a similar, though less pronounced, relationship between contrast discrimination and +Gx. As in Part II, Figure I-12 was used to correct for the use of a 50% detection threshold in obtaining the data. The results are shown as the visual acuity and visual contrast curves of Figure III-5. The probability of detecting the signal on the basis of at least one (contrast or acuity) component, $P(D_S)$, was then obtained using Eq. 1; the resultant plot of $P(D_S)$ as a function of +Gx is shown as the top curve in Figure III-5. Note that the function is similar to that obtained for reduced pO_2 on the basis of three components (Figure II-12); however, the +Gx function is higher initially and drops faster. There are no brightness discrimination data available for acceleration, so it is impossible to tell whether the initial difference in the hypoxia and acceleration functions are due to the missing component. The large drop in the acceleration curve, relative to the hypoxic curve, at low arterial O_2 values does indicate that acceleration has a more critical effect on the visual system than associated pO_2 levels.

II. Effects of +Gx on Attentional Processing

Bills' response blocking data (1937) have already been presented in relation to arterial oxygen saturation (Figure II-13). Figure III-6 presents the same data adjusted for the differences in effect of acceleration on blood saturation level. As before, it is the percentage increment in the duration of blocks that will be used to estimate the attentional effect.

III. Predicted Effects of +Gx on Performance

All predictions apply to exposures of 120 seconds. Where useable data are available, we have included them in the figures. For details of the methods used to calculate the predicted values, see Part I-Section VI and Part II.

A. Searching

(1) Search for one signal

Predicted search for one signal in a known position is shown in Figure III-7. It can be seen that although the curve drops rapidly, it remains in the acceptable zone before it reaches the first physiological limit. Search for one signal given N=1, 2, 3, 4, or 5 possible signals is shown in Figure III-8. The associated unacceptable zones are indicated. In neither case are data available.

(2) Search for multiple signals

The predicted effects of +Gx on multiple signal detection are shown in Figure III-9. As above, no data are available.

B. Switching

The predicted switching performance as a function of +Gx is shown in Figure III-10 for tasks with one possible signal presented in a known position, and in Figure III-11 for search involving one of N possible signals. Figure III-12 compares the predicted +Gx effects on simple switching, on a switching task for one signal presented in an unknown position, and on a switching task for one signal given two possible signals. The plotted data points for simple RT were taken from Kaehler and Meehan (1960) and corrected to equate their normal value with ours (RT≈.2). It may be seen from Figure III-10 that the predicted simple reaction time is a reasonable first approximation of the data. Figure III-12 shows that portions of the data fit the unknown position case equally well. In spite of this error, where the two predicted curves diverge the known position case does make the better prediction.

Predictions for tasks involving multiple signal presentations are shown in Figure I-13. No data are available.

C. Coding

Predicted percent correct coding as a function of +Gx is plotted in Figure III-14 for two levels of category complexity and two stimulus durations. No coding data are available.

D. Tracking

Figure III-15 presents the predicted relationships between human transmission lag, RT_T, and +Gx. The predicted performance levels for various measures of tracking are shown in Figure III-16. In evaluating the fit of the predictions to the data shown, it is very important to consider the large discrepancies between the conditions of gathering the data and the constraints imposed by our use of a 120 second exposure duration. None of the data shown were of this sort. Furthermore, the Kaehler data and the Clark data were obtained as -Gx and the Chambers data are based upon the extraction of one-axis data from a task situation in which the subject actually tracked in three axes. Given these discrepancies among the obtained data, it is difficult to evaluate the goodness of our predictions. On the other hand, it appears clear that, except for Kaehler's data, our predictions overestimate the effects regardless of the discrepancies among experimental conditions. This is not true of our predictions regarding the effects of reduced pO_2 (Figure II-37), as the predicted values do fit the data with a reasonable approximation. We conclude, therefore, that the basis of the predictions requires further theoretical work concerning the effects of +Gx on RT_T. Specifically, the curve shown in Figure III-16 must be improved.

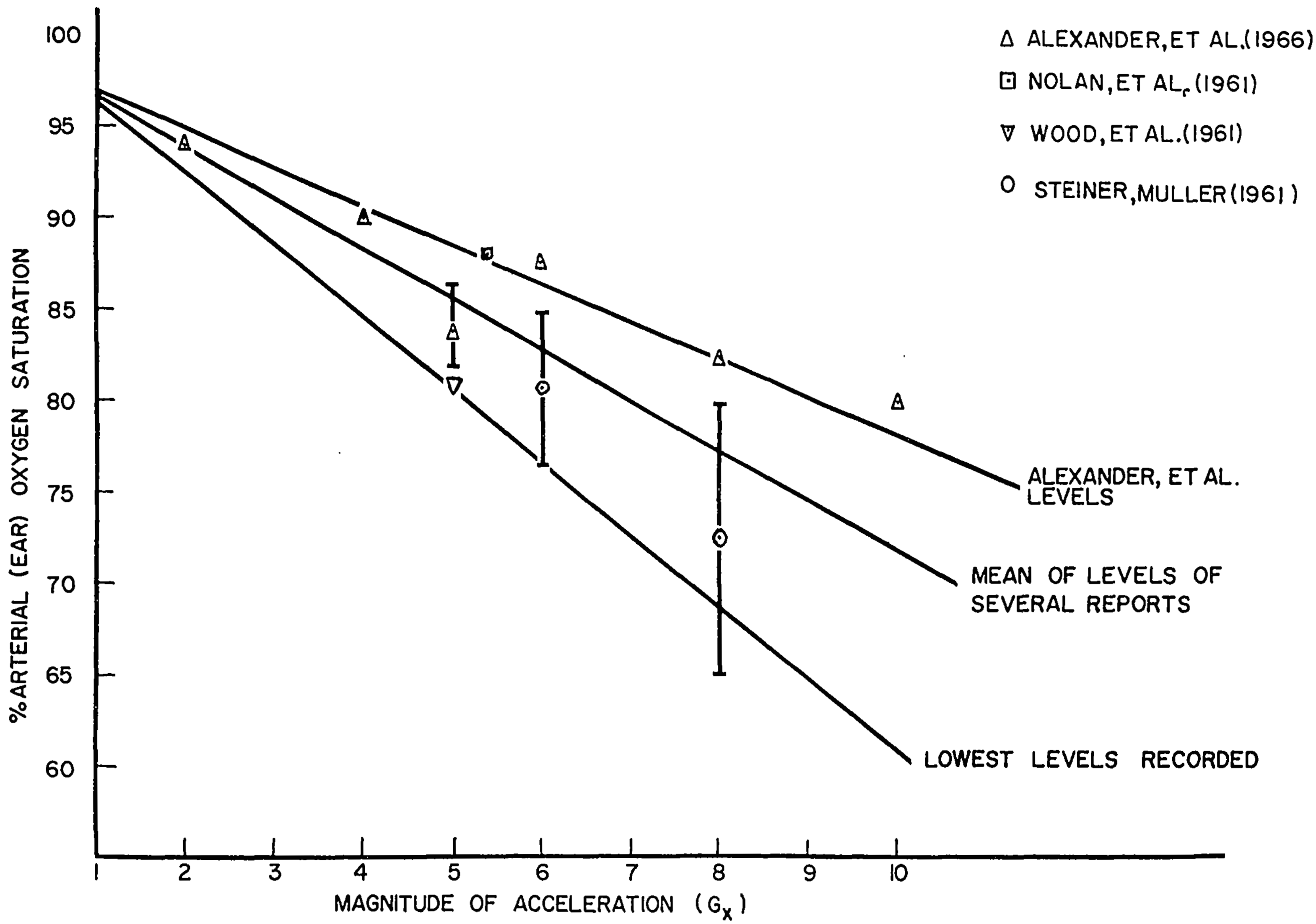

FIG. III-1 Arterial Oxygen Saturation at $+G_x$ for 120 Seconds Breathing Air. Adapted from Teichner, Craig and Tompkins, 1966.

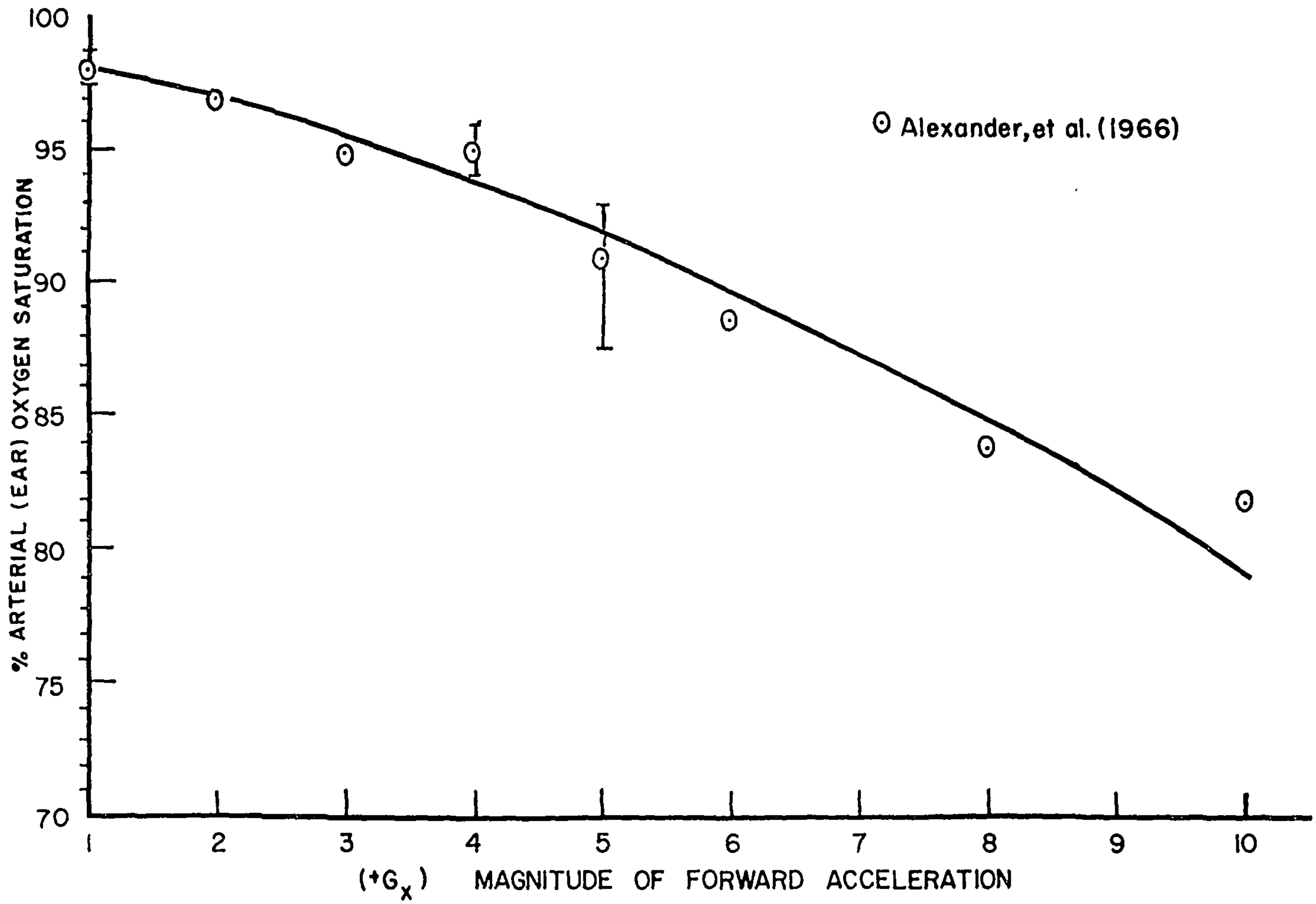

FIG. III-2 Arterial Oxygen Saturations at $+G_x$ for 120 Seconds while Breathing 100% Oxygen at 5 psia. Teichner, Craig and Tompkins, 1966.

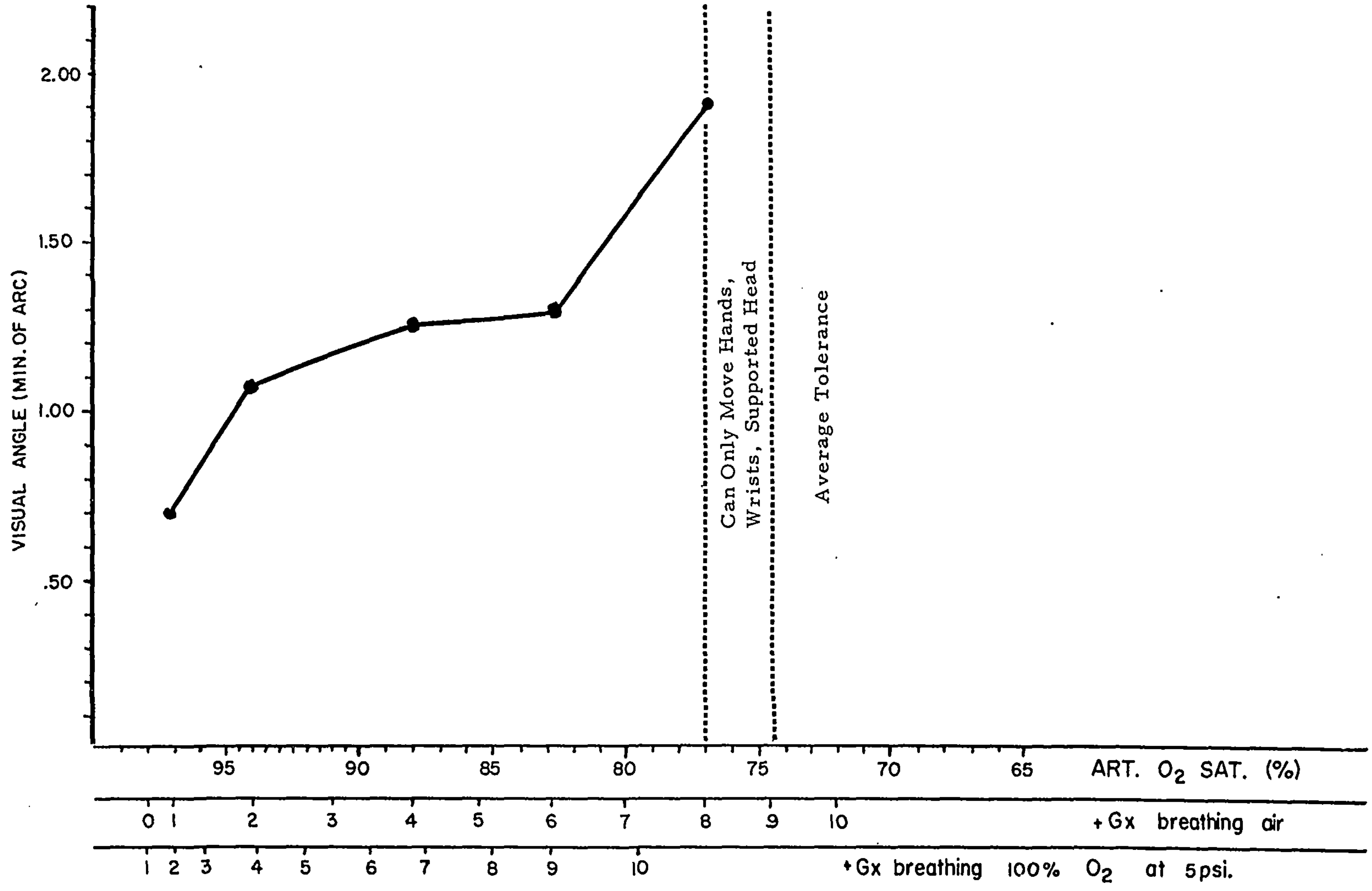

FIG. III-3 Binocular Visual Acuity (Min. of Arc.) as a Function of $-G_x$. From White and Jorve, 1956.

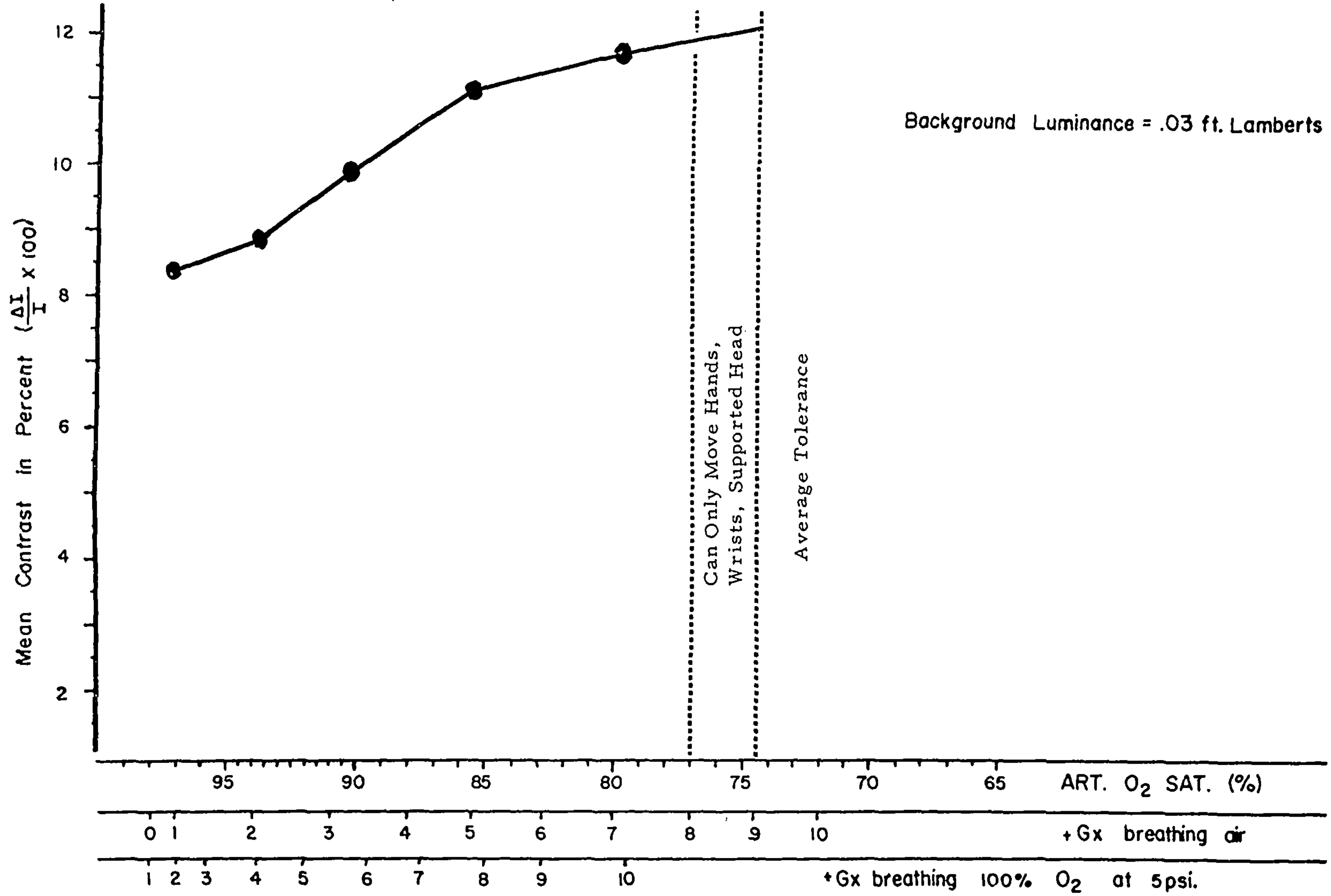

FIG. III-4 Contrast Discrimination ($\frac{\Delta I}{I}$ x 100) as a Function of $+G_x$. Data from Chambers et al 1962.

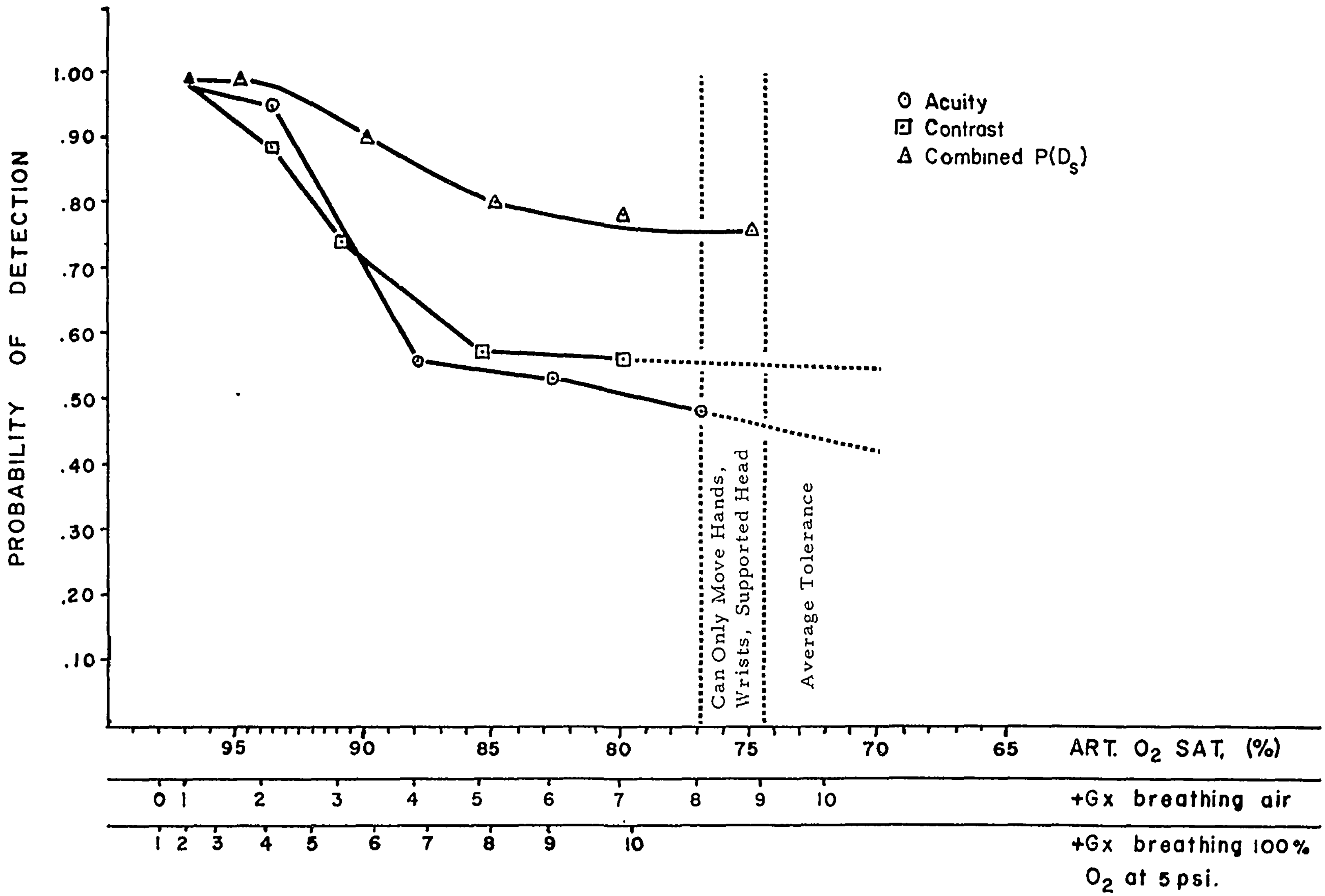

FIG. III-5 Probability of Detecting a Signal on the Basis of only 1 Cue. Probability of Detecting a Signal on the Basis of Either Cue $(P(D)_s)$

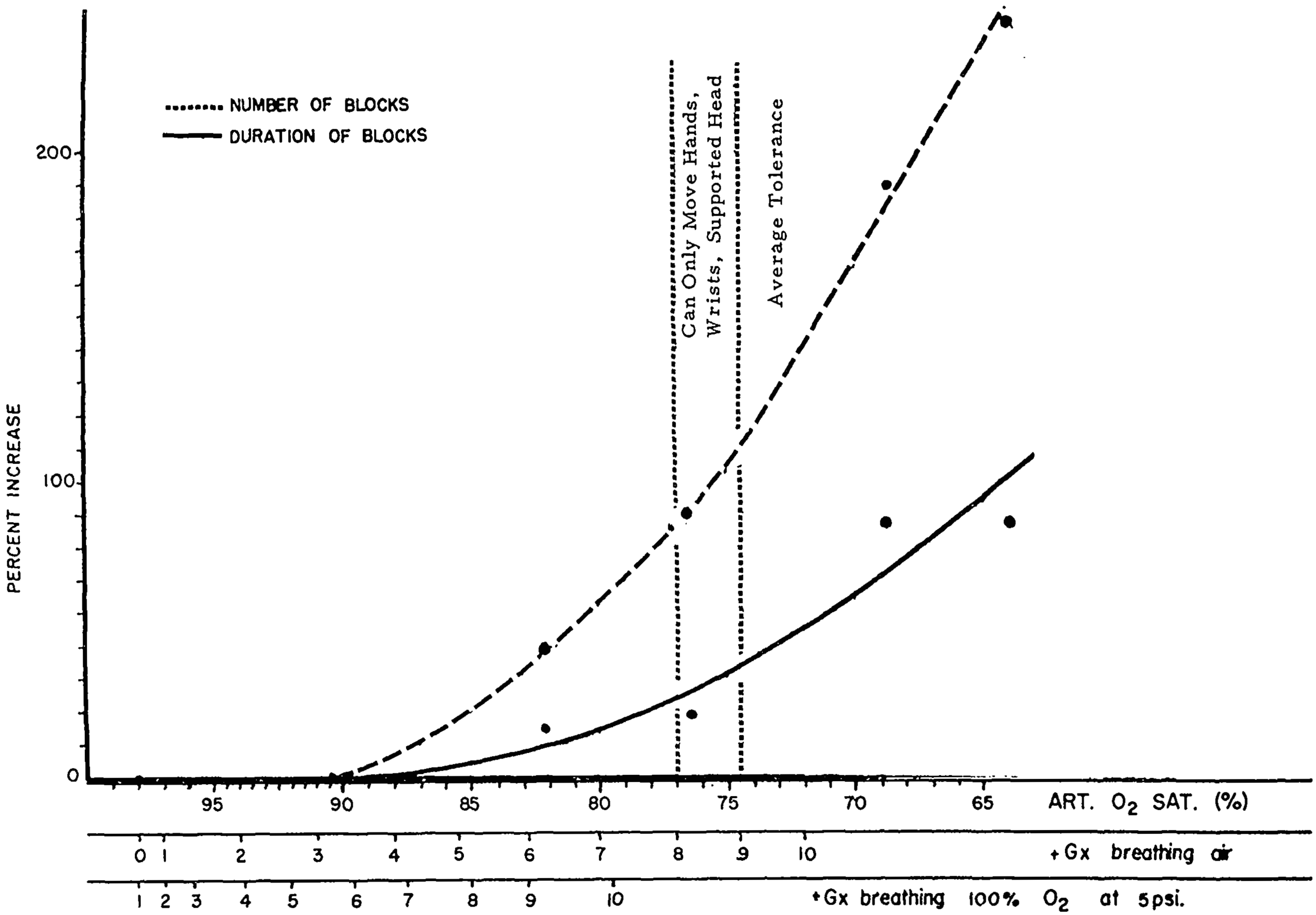

FIG. III-6 Expected Effects of G_x on Response Blocking.

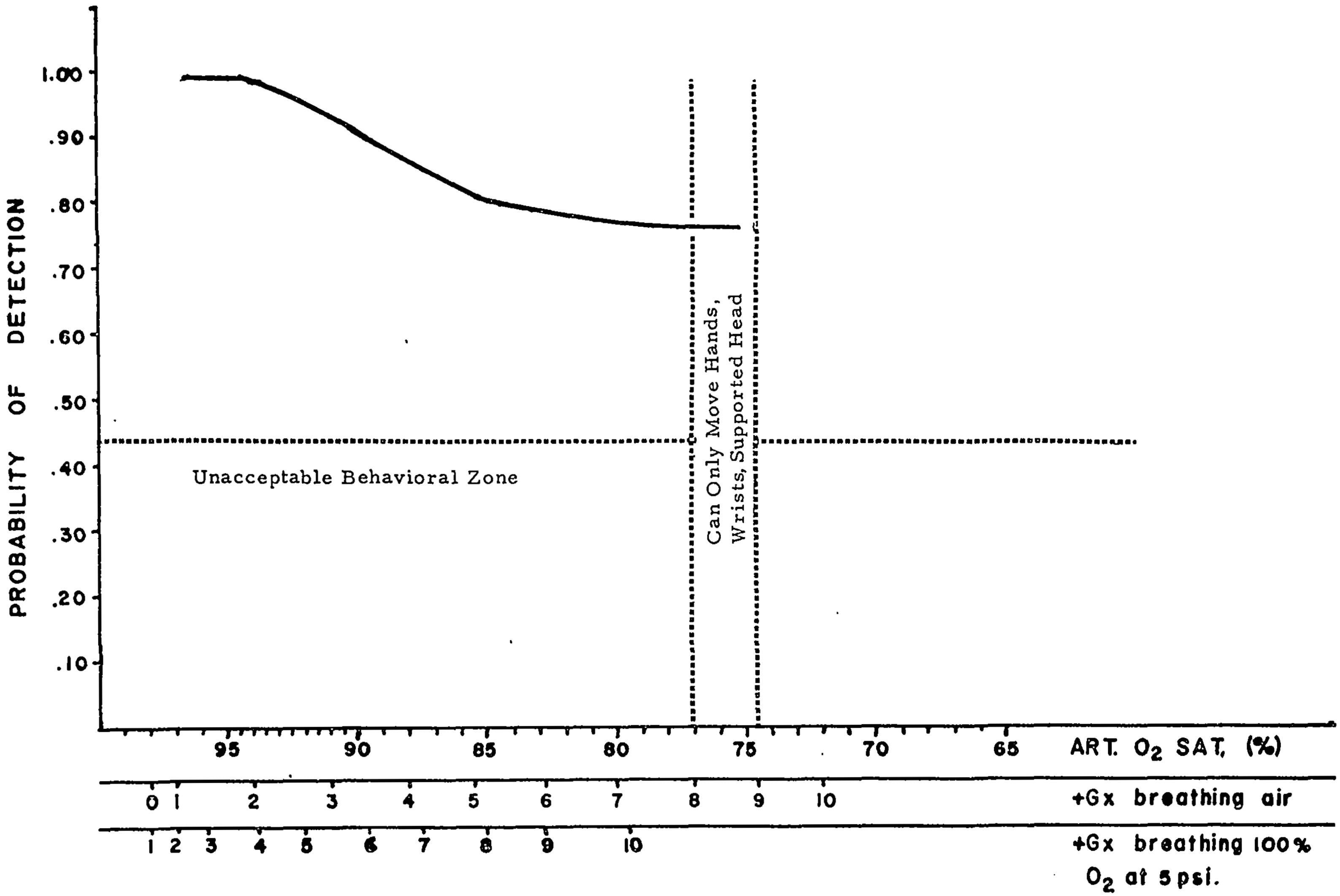

FIG. III-7 Predicted Search for One Possible Signal Arriving at a Known Position but at an Unknown Time, as a Function of G_x.

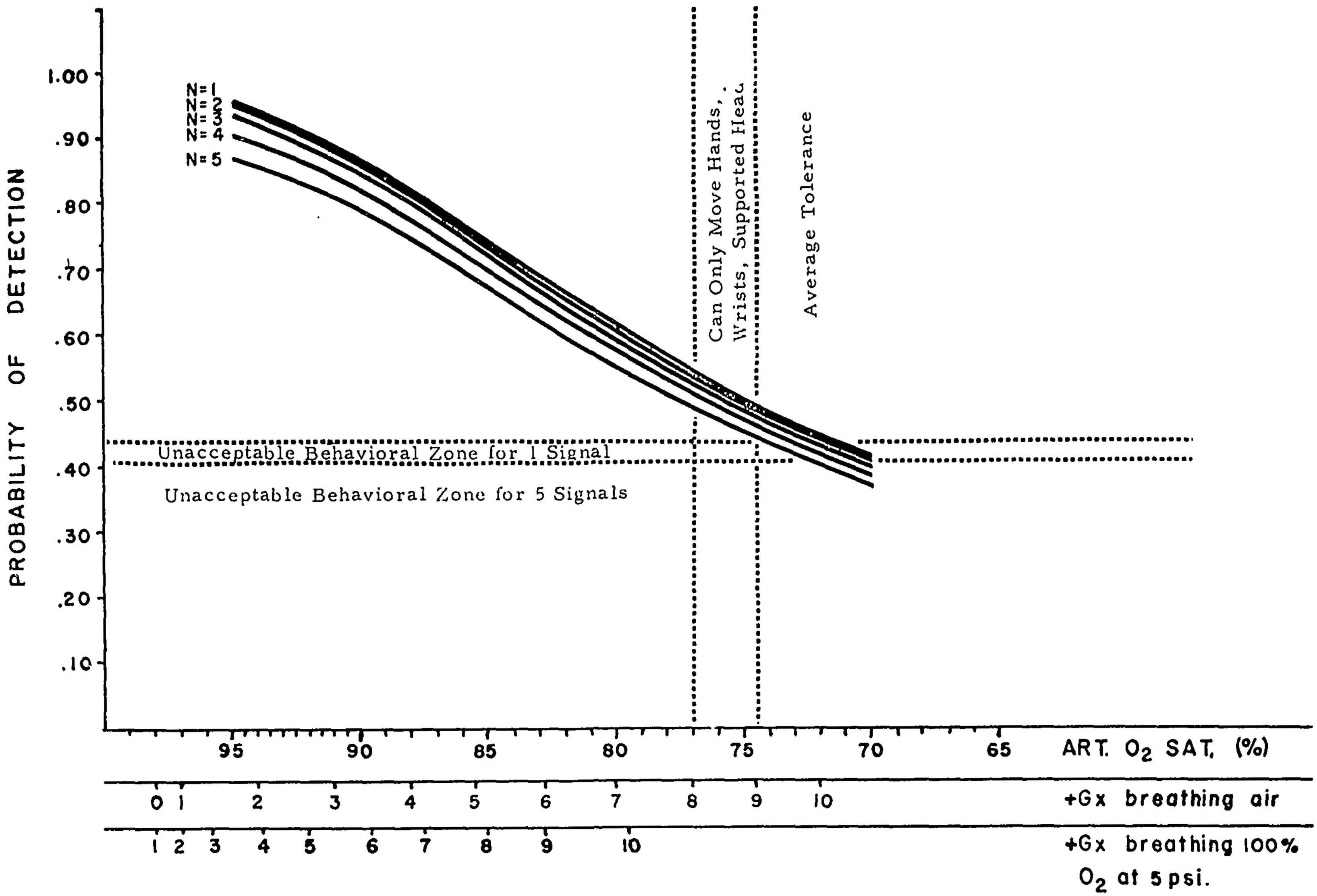

FIG. III-8 Predicted Search for One Signal of N Possible Signals, as a Function of G_x. The Signal Arrives at an Unknown Time and Position.

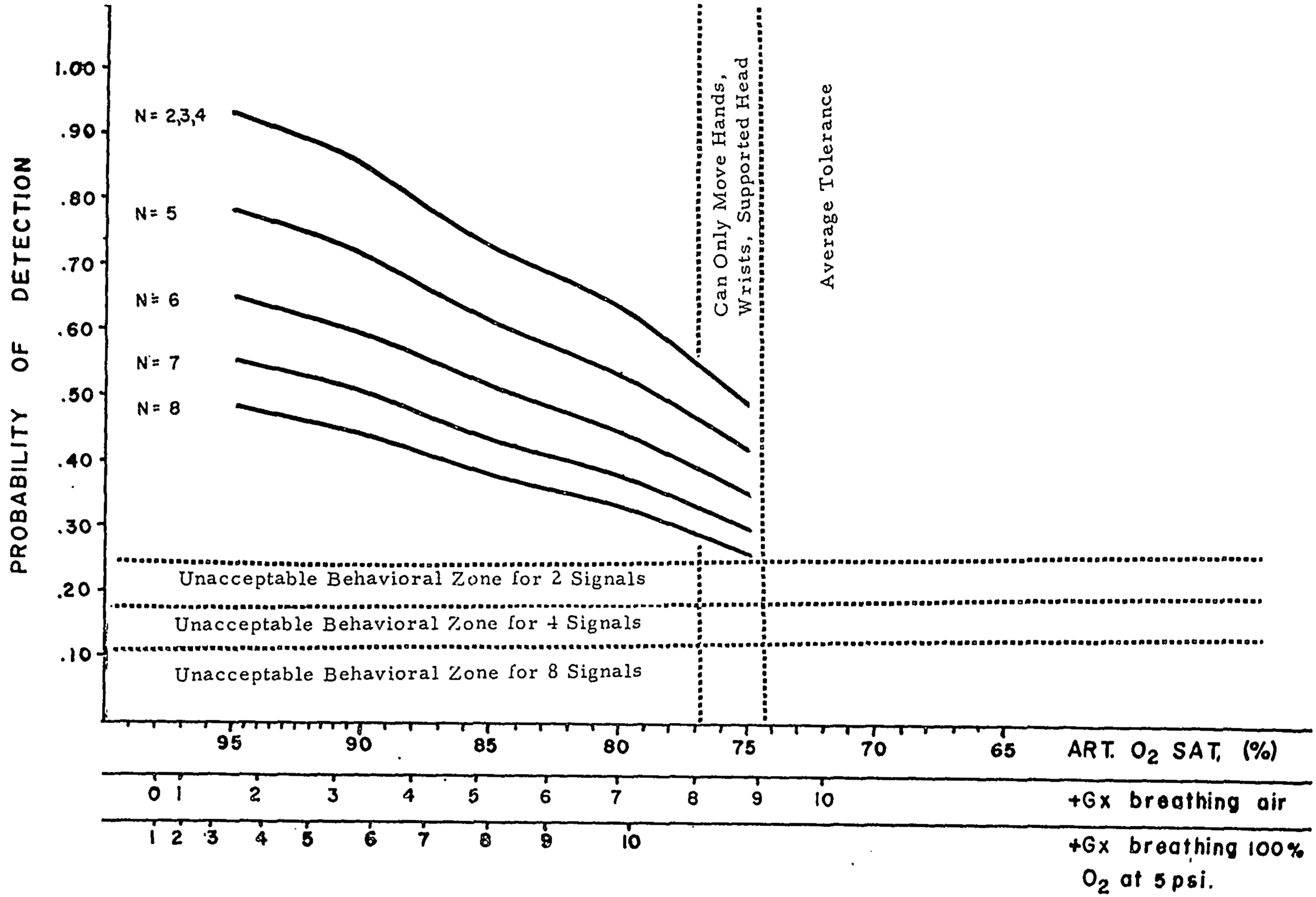

FIG. III-9 Predicted Search for N Simultaneously Presented Signals as a Function of G_x.

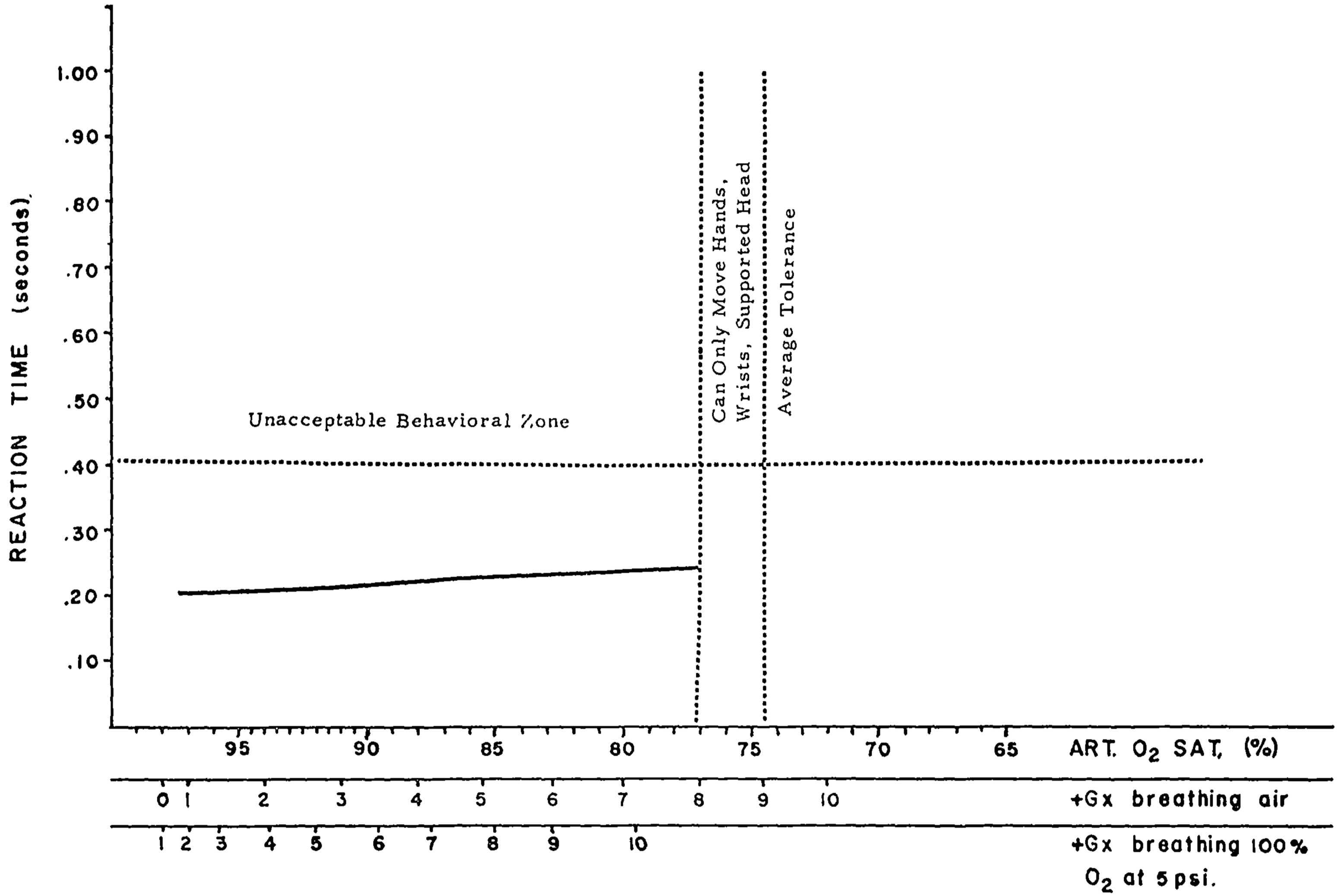

FIG. III-10 Predicted Simple Switching as a Function of G_x.

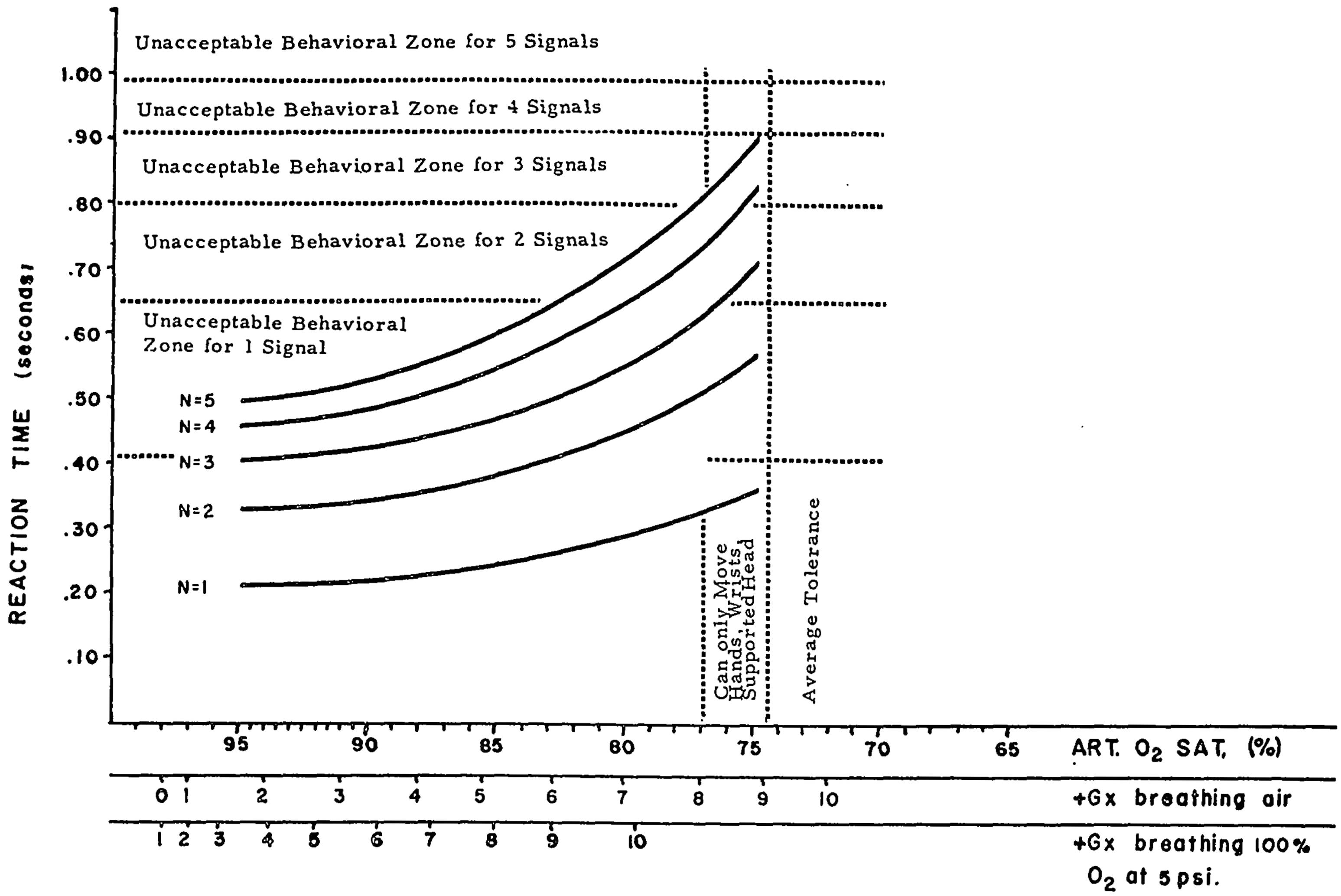

FIG. III-11 Predicted Switching for One Signal Given N Possible Signals as a Function of G_x. The Signal Arrives at an Unknown Time and Position.

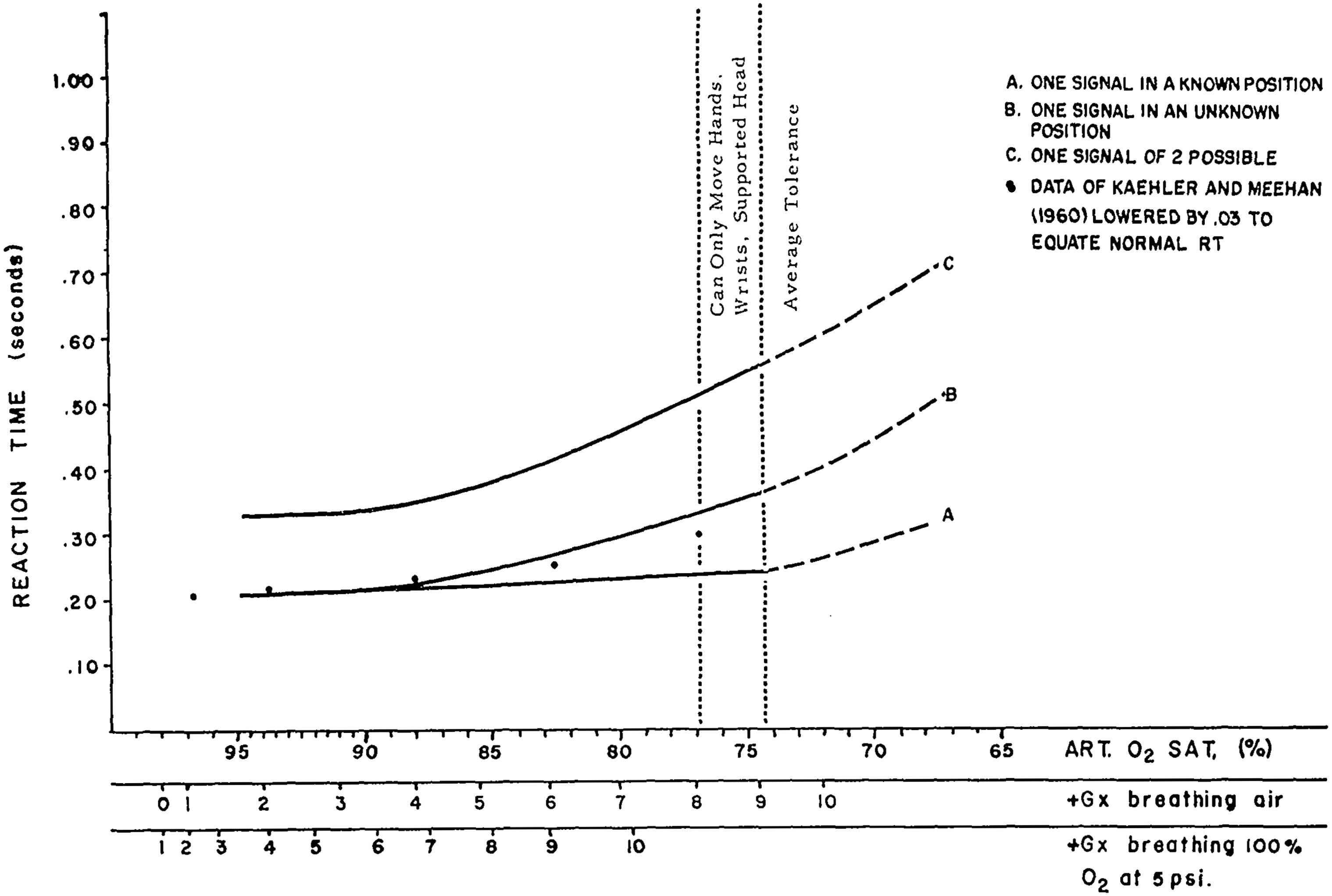

FIG. III-12 A Comparison of the Predicted Effects of G_x on Performance of Three Different Switching Tasks.

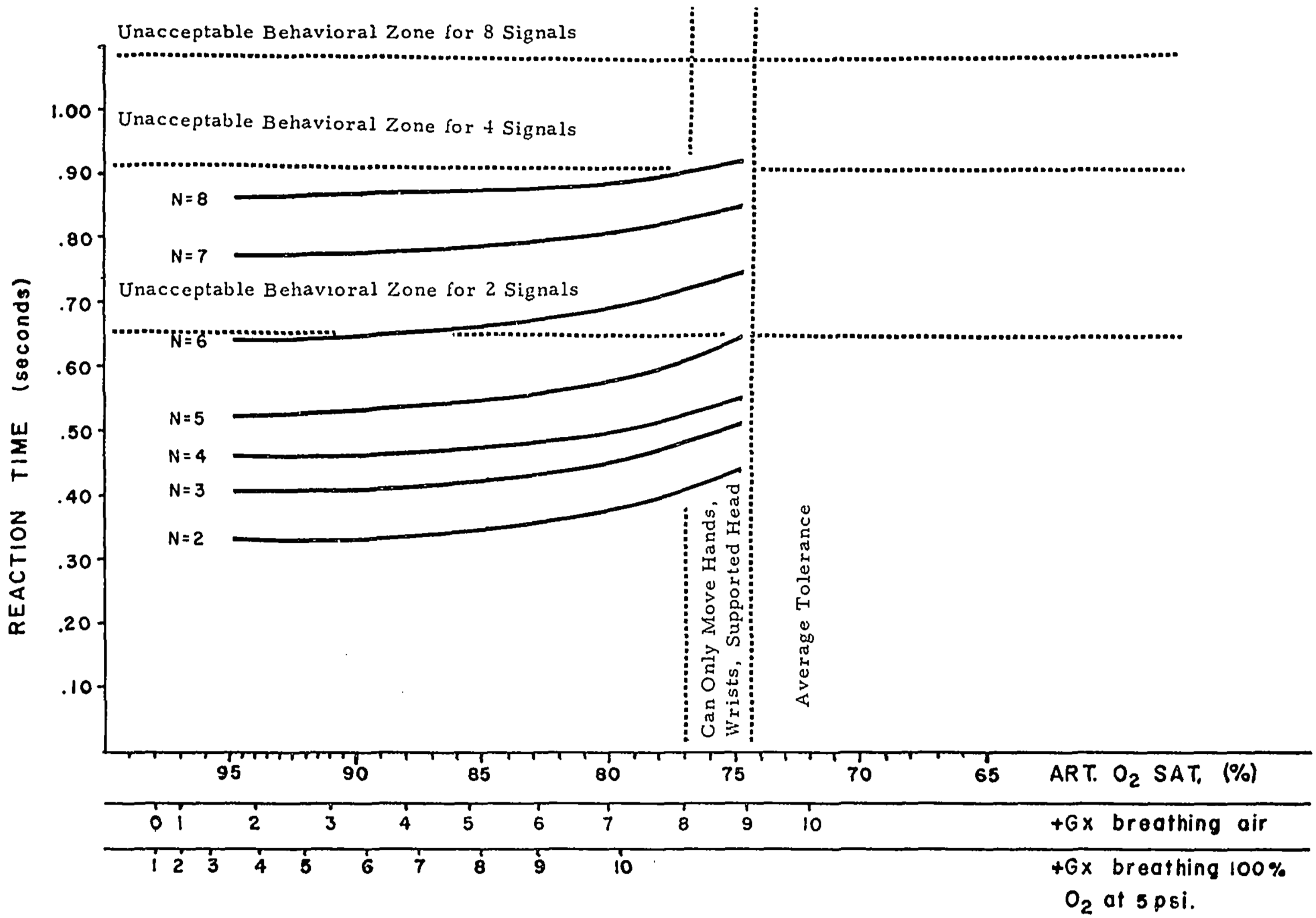

FIG. III-13 Predicted Effects of G_x on Switching for Tasks with N Simultaneously Presented Signals.

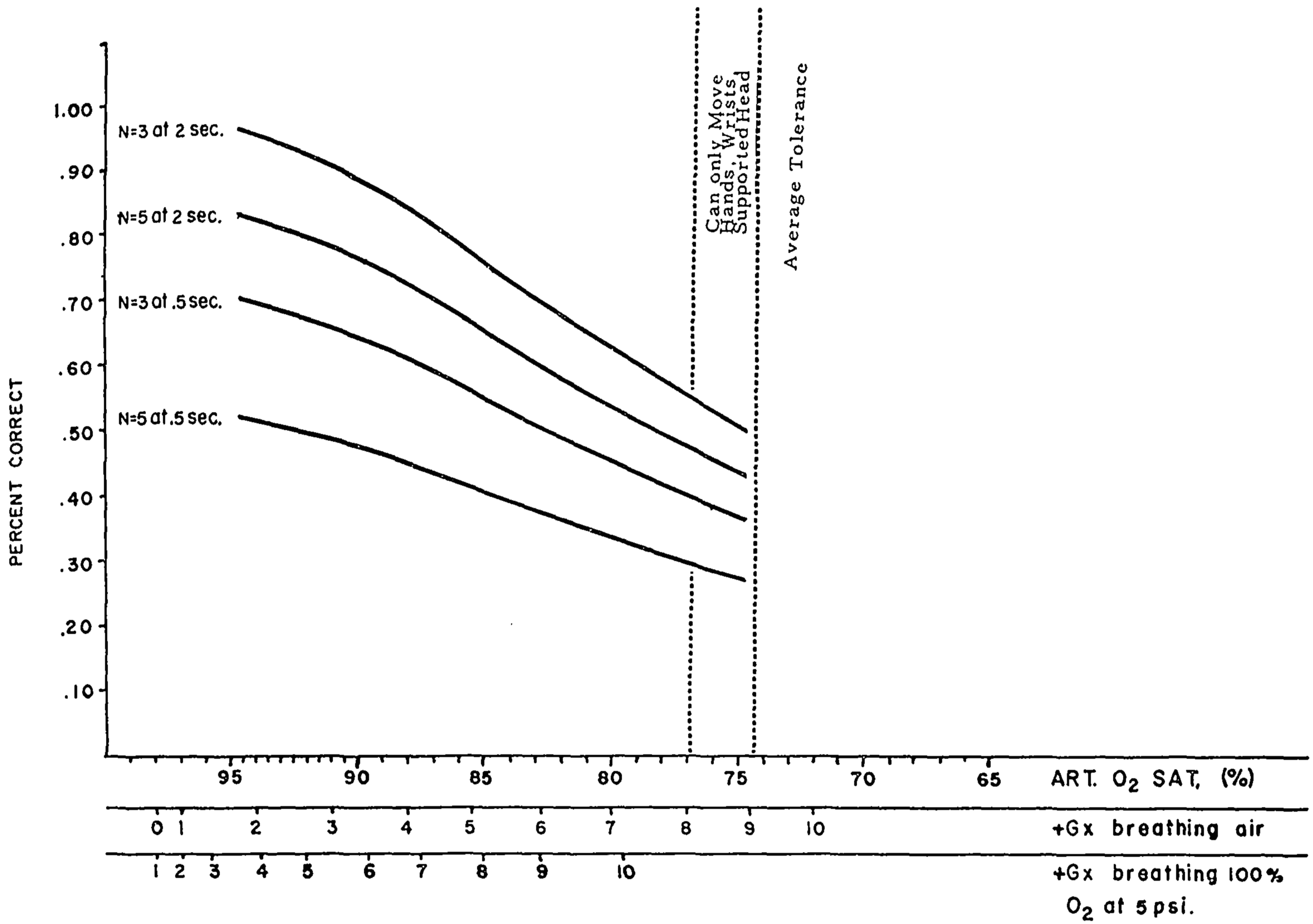

FIG. III-14 Predicted Effects of G_x on Coding of Three and of Five Simultaneously Presented Signals with Durations of .5 and 2 Seconds.

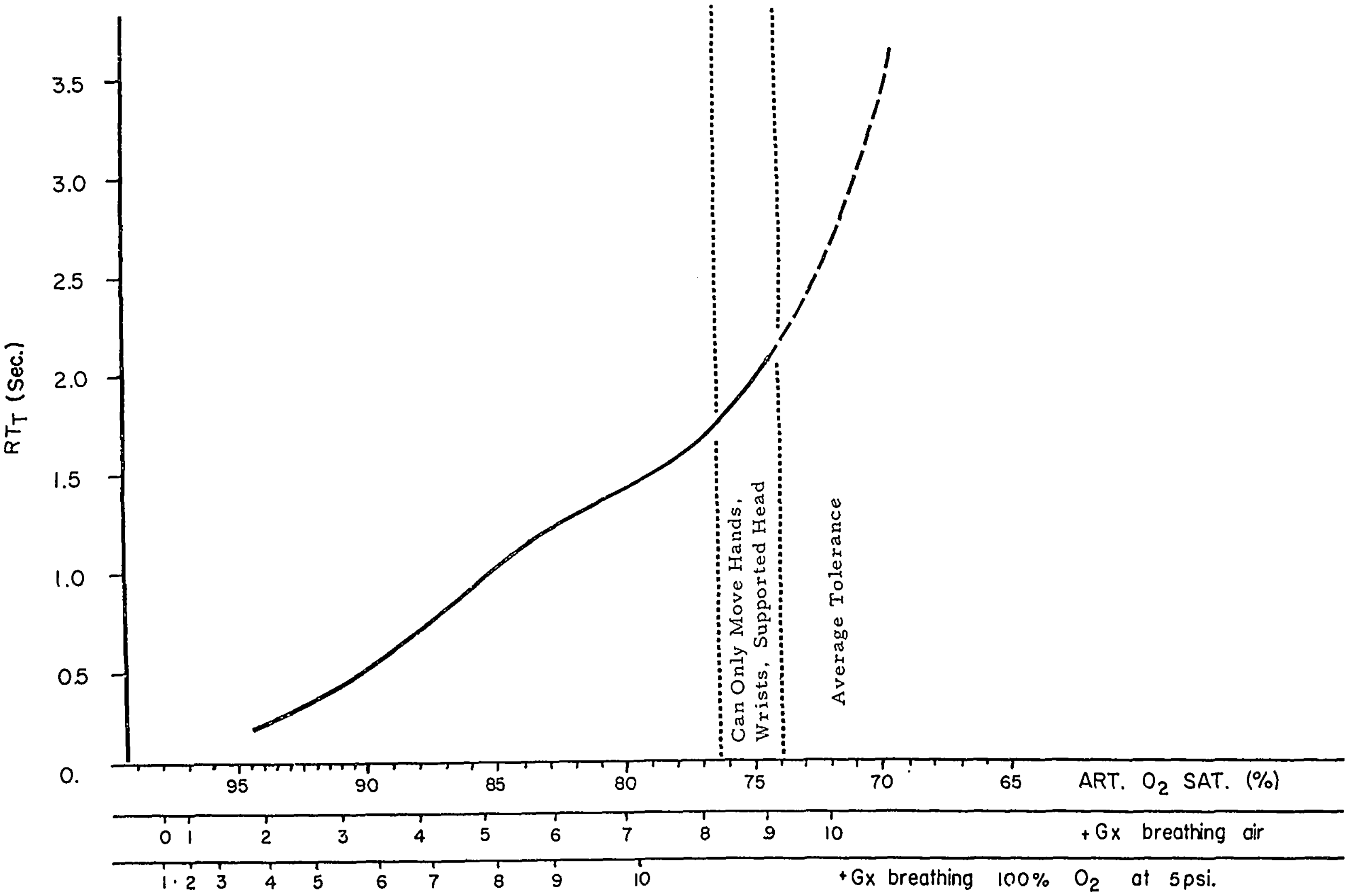

FIG. III-15 Predicted Relationship Between Human Transmission Lag, RT_T, and G_x.

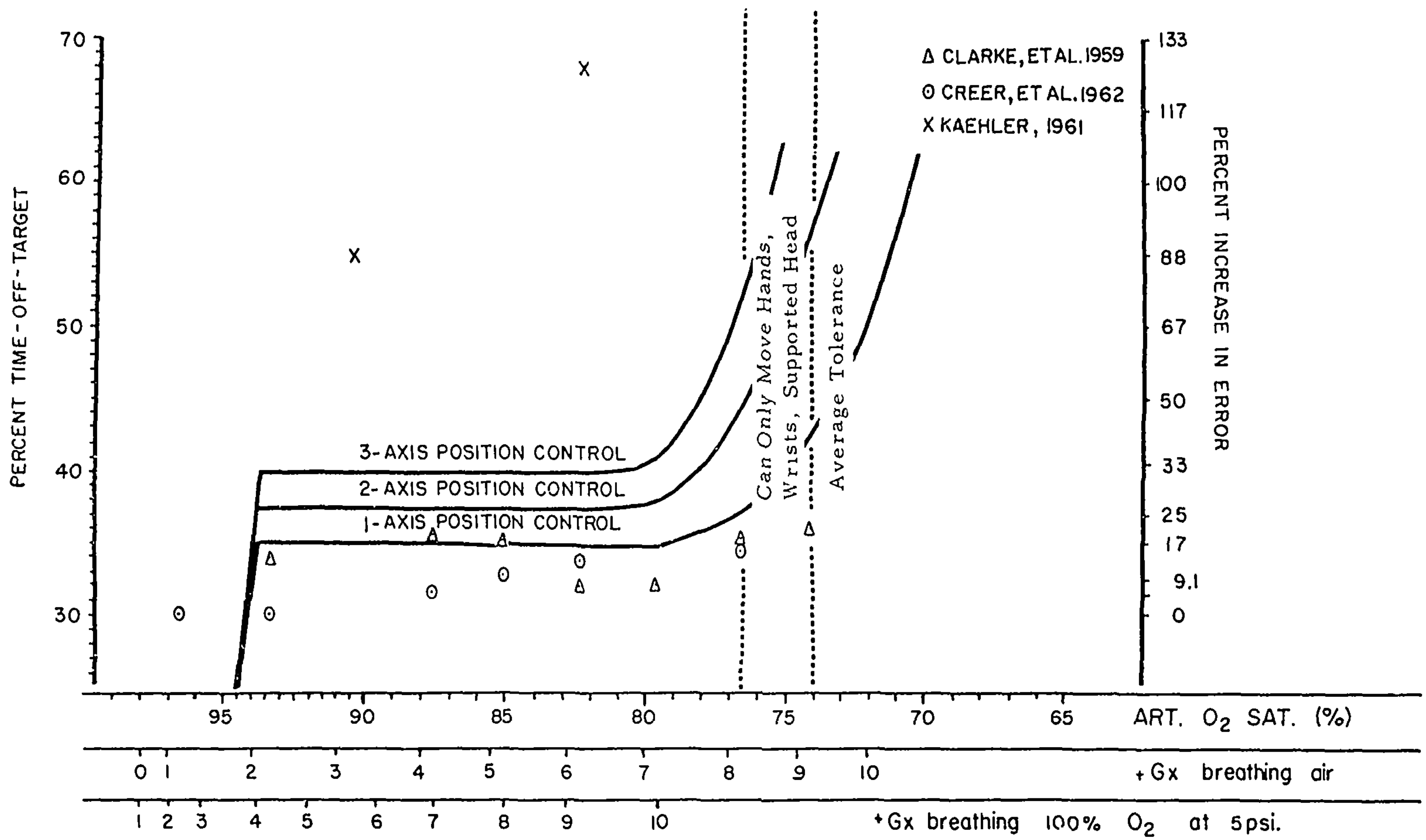

FIG. III-16 Predicted Effect of G_x on Tracking Performance.

Predicting Human Performance in Space Environments

IV. Other Environments

In this part of the report we shall discuss the problems of predicting performance in relation to temperature, noise, and other environments. The presentation will be incomplete in the sense that we shall not present the prediction graphs for these environments as we have done in the last two sections. Rather, for temperature and noise we shall present functions which, if desired, may be employed to make the predictions using the procedures explained in Parts I and II. Discussion of the other environmental factors will be more general.

I. The Thermal Environment

The most important first consideration in dealing with the effects of the thermal environment is the question of definition. That is, although the thermal environment is described in terms of temperature, humidity, air movement, and radiation, people working in the environment wear clothing. As a result, the actual thermal environment is the "microenvironment" existing between the clothing and the skin, except for the face and hands which may (or may not) be directly exposed. For this reason it is very misleading to express relationships between a measure of performance or of physiological state and the external environment (or macroenvironment). Some useful approximation may be obtained by describing the external environment and the garb of the individual as "lightly clothed" etc., but much greater meaning and utility lies with the use of physiological measures as independent variables. Then any combination of clothing and thermal environment may be expressed in terms of resultant physiological levels. Actually, this approach is in complete agreement with our previous use of arterial oxygen saturation as an equivalent for pO_2. In the present case, however, the selection of a physiological phenomenon is not as easy.

The problem is complicated further by the fact that very few of the performance studies available have taken physiological measures, nor has careful consideration been given to conditions of clothing and muscular effort. Therefore, in order to obtain relationships,it is necessary to make a careful analysis of the few physiological studies in which clothing, exercise and environment were studied,and then to generalize the physiological levels to performance studies in which they were not considered.

A. Physiological Equivalence

We are interested in relating performance to those levels of physiological-environmental variables at which thermal balance can be maintained. Undesirable physiological effects fall beyond these limits. A wide variety of physiological measures has been related systematically to variations in the environment, e.g. oxygen consumption, metabolic rate, minute volume, heart rate, rectal temperature, skin temperature, etc. Unfortunately, these measures taken singly have not been shown to be correlated with performance within our range of interest,except for what is essentially exercise. For this reason, in order to deal with the problem it is necessary to approach body heat regulation as a system rather than in terms of ony one of its parameters.

The major elements of the thermoregulatory system are: (1) metabolic heat production (H), (2) the circulatory transfer of heat from the interior to the surface, (3) the transfer of heat between the surface and the environment. Without going into details, it is apparent that a measure which is a function of the heat production and the temperature gradient from the interior (or core) to the surface will reflect the (non-evaporative) state of body regulation at any time. The circulatory convection index provides such a measure, i.e.

$$C = (H/Tb-Ts)-k \quad KCal/M^2/hr/^{\circ}C$$

where C = the circulatory convection index, also called the tissue heat conductance

H = total heat production in $KCal/M^2/hr$

Tb = internal body temperature (rectal) in $^{\circ}C$

Ts = mean body area weighted skin temperature in $^{\circ}C$

k = the specific conductance of the tissue which can be taken as 9.1 $KCal/^{\circ}C/M^2/hr$.

The quantity (Tb-Ts) is a gradient of temperature from the core to the surface. Thus, as H becomes larger relative to the gradient, heat is being produced and stored internally at a rate greater than it is being transferred to the surface. The associated bodily state is a peripheral vasodilatation representative of warm environments. Conversely, as H becomes smaller relative to the thermal gradient, heat is being transferred to the surface faster than it is being stored, a condition characteristic of the cold and associated with a peripheral vasoconstriction. When the numerator and denominator are equal, the body is in heat balance. This model has been developed in slightly different form and used by a variety of investigators over many years, in particular to study cold exposures. We shall attempt to use it for both heat and cold exposures. Future study of this problem should further investigate this approach, as well as others (e.g. body heat storage).

The quantity, C, has a variety of weaknesses for the study of thermoregulation. Among them is its low validity under conditions which are associated with important amounts of evaporative heat loss. Fortunately, for our purposes these are conditions which are less important to us as they approach or exceed physiological limits. For the present purpose our primary interest is in the range of C within which rectal temperature varies little and active sweating is small. Two other qualifications for the use of C must be made. Although thermal regulation is affected markedly by levels of exercise, i.e. by the effort levels involved in the task, the tasks which we have been considering involve negligible muscular effort, (maximum of 200 $KCal/M^2/hr$) so this problem is of little concern. Similarly, the level of clothing must be accounted for as it affects the time function of C. We are concerned with the shirt-sleeves environment, i.e. we are assuming light clothing or its physiological equivalents.

Proper determination of C requires obtaining H (usually by indirect calorimetry), Tb and Ts. No performance studies are available which have obtained all of these measures; in fact, there are few studies which have obtained any one of them. To obtain estimates of C, an indirect approach must be found. Fortunately, the mean weighted skin temperature provides a good, though non-linear, estimate as shown in Fig. IV-1. The figure shows C for the supine individual at rest and at light work both in the short-sleeve condition. The upper, light-work, curve is the basic curve to be used in the present feasibility study. That is, using this curve, a given mean weighted skin temperature may be used to obtain an estimate of C. Skin temperature may be estimated from a variety of sources, e.g. the Compendium of Human Responses to the Aerospace Environment, Vol. II (cf. Figures VI-61, 62, 63). The skin temperature associated with any combination of environment, clothing, and exercise could be taken to obtain C, except that C varies within an environmental level depending on the levels of exercise and the conditions of clothing.* The safest use of C, then, using a skin temperature estimate is for the conditions indicated, viz. light clothing, light effort, and equilibrium exposure (1-2 hr. before the start of the task).

B. Sensory Effects

Our selected modality for this feasibility study is vision. There is no acceptable experimental basis for assuming that the thermal environment affects visual function; therefore, we need not develop predictions based upon expectations of such a loss. Tactual sensitivity is markedly affected by low temperatures and tasks which involve this sensitivity, such as tactual coding, will be severely affected as the hand skin temperature decreases. (60° F may be taken as the hand skin temperature at which the tactual loss is initiated if the rest of the body is warm) Figure IV-2 presents an hypothesized relationship between mean weighted skin temperature and percent decrement in tactual sensitivity. Assuming bare hands at the indicated total surface levels, the decrements may be applied to normal performance in tasks which require fine tactual sensitivity. A more appropriate, but presently unmanageable, approach would deal with the tactual stimulus in the same way that we have dealt with the visual one.

*Actually, no good set of curves for C, skin temperature, etc. are available. The data needed to develop them do appear available.

Grosser hand manipulations are also affected in the cold, but as the result of a reduction in the viscosity of joint fluids. The "gross dexterity" curve in Fig. IV-2 presents the percent decrements to be applied for this purpose. In this case, the percent decrement can be subtracted after all of the considerations described earlier (Part I, Section VI) for predicting performance, or it can be used by adding the appropriate value from this curve to the attentional loss value to be described next. An important caution at this point is that use of the gross manual performance decrement assumes that the individual will carry out the task exactly the same way as he would under normal environmental conditions. In fact, in the cold he is likely to use a new kind of manipulation technique. If so, the decrement curve does not apply.

C. Attention

Aside from the encumbrances of clothing and the impairment of body joint flexibility, temperatures within our range of interest appear to affect only the attentional mechanism. Presumably the effect is through the activating mechanisms. There are no response blocking data to apply to this environment. It is necessary, therefore, to estimate the attentional loss by some other means. We have done this via a variety of experimental results and logical considerations. The result is a tentative percent decrement curve (or estimated increase in response block duration) for the heat and the cold as shown in Fig. IV-3. The baselines show the relationship between mean weighted skin temperature and tissue heat conductance (C) which is the variable of real interest.

D. Predictions

Predictions may now be made by following procedures described in Part I. All predictions assume no visual sensory loss. Where the task is continued for some time, Fig. I-8 again provides reduced P(D) at different time periods. Figure IV-3 provides the attentional factor comparable to Fig. II-13. Again, the predictions assume that the subject has been in this environment for at least one or two hours before the start of the task.

II. The Acoustic Environment

In this section we are dealing with the effects of nonsymbolic sound, or noise, on performance. Within our range of interest, below the pain threshold, the effects of sound seem to be entirely psychological except for a quickly completed auditory adaptation (Mirabella, Taub, and Teichner, 1967; Teichner and Sadler, 1966). Those physiological effects which appear with the onset and offset of sound habituate and, although they may be related to annoyance, function mainly as distractors. In our terms, the attentional filter may be wider than optimal during this period, but habituation is rapid and the filter narrows again. The problem of predicting performance with noise requires specifying: (1) whether the noise is intermittent or continuous, and (2) whether it is expected or unexpected. In all cases, the result should be a widening of the attentional bandwidth and responses to the irrelevant sound. This effect should decrease faster for steady and for expected sounds.

As with the thermal environment, no visual effect need be anticipated. The direct masking effects of sound are well documented and need not concern us here. Furthermore, we need not obtain a physiological effect of the environment since there is none. Then, the effects of noise can be accounted for in terms of normal performance weighted by factors of attention and habituation.

Some question arises with regard to the effect of sound pressure level. It is reasonable to assume that the higher the pressure level the greater should be the <u>initial</u> attentional loss. The effect of intensity is likely to be less important for the unexpected sound since such a sound has high alarm or activation value regardless of its intensity. In the case of the expected sound the effect may be small; for now we shall ignore it.

There are a variety of ways in which we might try to develop an attention-habituation function; unfortunately, we do not at this writing have an experimental basis for selecting functions for most of these methods. Further study of the literature might reveal such bases. Meanwhile, we have selected a study by Mirabella, Taub, and Teichner (1967) which has reported the habituation effects of continuous and fluctuating sounds. On the basis of their results (cf their Experiment IV) we have assumed complete habituation to steady sound, and incomplete habituation to fluctuating (or mixed or rapidly intermittent) sound. We have taken the maximum degree of habituation found with steady sound in their study to represent complete habituation. Using that maximum as a referent, we have generated the predicted relationships between percent attentional loss and time of onset of unexpected sounds (Fig. IV-4). In order to generate these curves we adjusted the results somewhat both to make the attentional loss less drastic and to smooth the curves. The curves for "expected" sounds and all values beyond 20 minutes were postulated. This figure, then, may be used as the attentional loss curve comparable to the response blocking curve of Fig. II-13 except in this case the environmental levels are expressed in terms of time. Note that the time measure here is time of environmental exposure, rather than time at a task. In order to account for loss in P(D) due to time at task, Fig. I-8 should be used as before.

A final comment is worth making about Fig. IV-4. We have assumed that the sound itself has no particular effect, but rather that it acts as an irrelevant signal which is particularly effective when it is unexpected. Thus, the figure really represents the hypothesized effect of any form of noise, e.g. tactual, vibratory, thermal, which has no resemblance to the task stimuli.

III. Remaining Environmental Factors and Concluding Remarks

We emphasize once again that this is a feasibility study. Its purpose has been to explore the utility of an approach which:

1) Recognizes the lack of information with which to develop a general predictive system.
2) Attempts to make the most of what is available, and
3) Attempts to generate reasonable assumptions to help bridge information gaps.

Even in doing this we have not explored the basic physiological and psychological literatures in sufficient depth to develop general relationships of the sort that we think we need. Such work must be done if the platform on which the predictions rest is to be as reliable as available science will permit. In lieu of this we have tended to use some of our own studies (since we are very familiar with them) and certain basic experiments which were easily available and easily convertible to our purposes. Nevertheless, we feel that much has been accomplished by way of showing that it is possible to make predictions at all and by way of revealing the kinds of information which are needed.

What we have done is to sample from general classes of environmental factors. Thus, reduced pO_2 represents the Atmospheric Environment; CO represents Contaminants; transverse acceleration represents the Mechanical

Environment within which falls vibration, motion, other accelerations, and weightlessness. Not yet discussed are Illumination and Ionizing Radiation. The former has not been ignored since within the present context we have concentrated on tasks employing visual signals. If the illumination is low, P(D) will be affected and these effects are predictable within our basic postulates. Ionizing radiation is a great unknown although there is, perhaps, enough known now to hazard some hypotheses about physiological effects and go on from there. However, within the present context of Apollo, it is our understanding that doses which will affect performance <u>within the time span of the mission</u> are not likely to occur. Severe doses will produce effects which reach physiological limits rapidly. Lesser doses may not show performance effects until after completion of the mission. Therefore, we have delayed approaching this problem.

Finally, it should be kept in mind that we have restricted our effort to visual signals which, although the most important in many ways, are not the only kinds of task signal. In particular, speech and other auditory signals may be critical and tactual signalling is also a possibility. Once sensory information is obtained for these modalities, we assume the best prediction methods will closely follow those we have presented for vision. To account for all possible tasks in all possible environments is, of course, a worthy goal--perhaps to be achieved by our descendants. Meanwhile, we feel that the utility of the kind of approximating and hypothesizing we have done should be extended, refined and investigated experimentally as rapidly as possible.

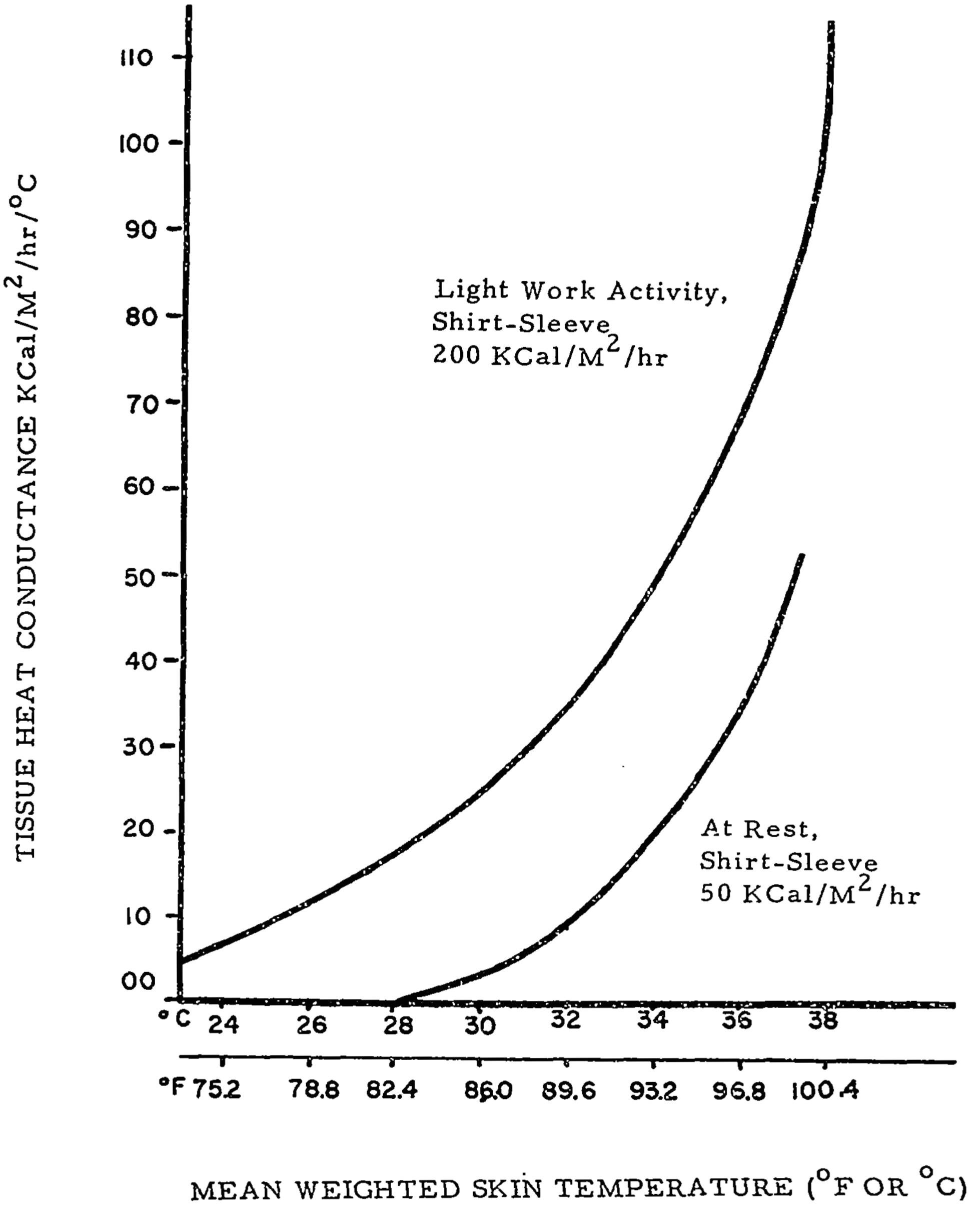

FIGURE IV-1. EQUILIBRIUM TISSUE HEAT CONDUCTANCE OR HEAT LOSS DUE TO CIRCULATORY CONVECTION RELATED TO SKIN TEMPERATURE, FOR TWO LEVELS OF ACTIVITY, BOTH WITH LIGHT (SHIRT-SLEEVE) CLOTHING. BASED ON DATA OF ROBINSON (1963).

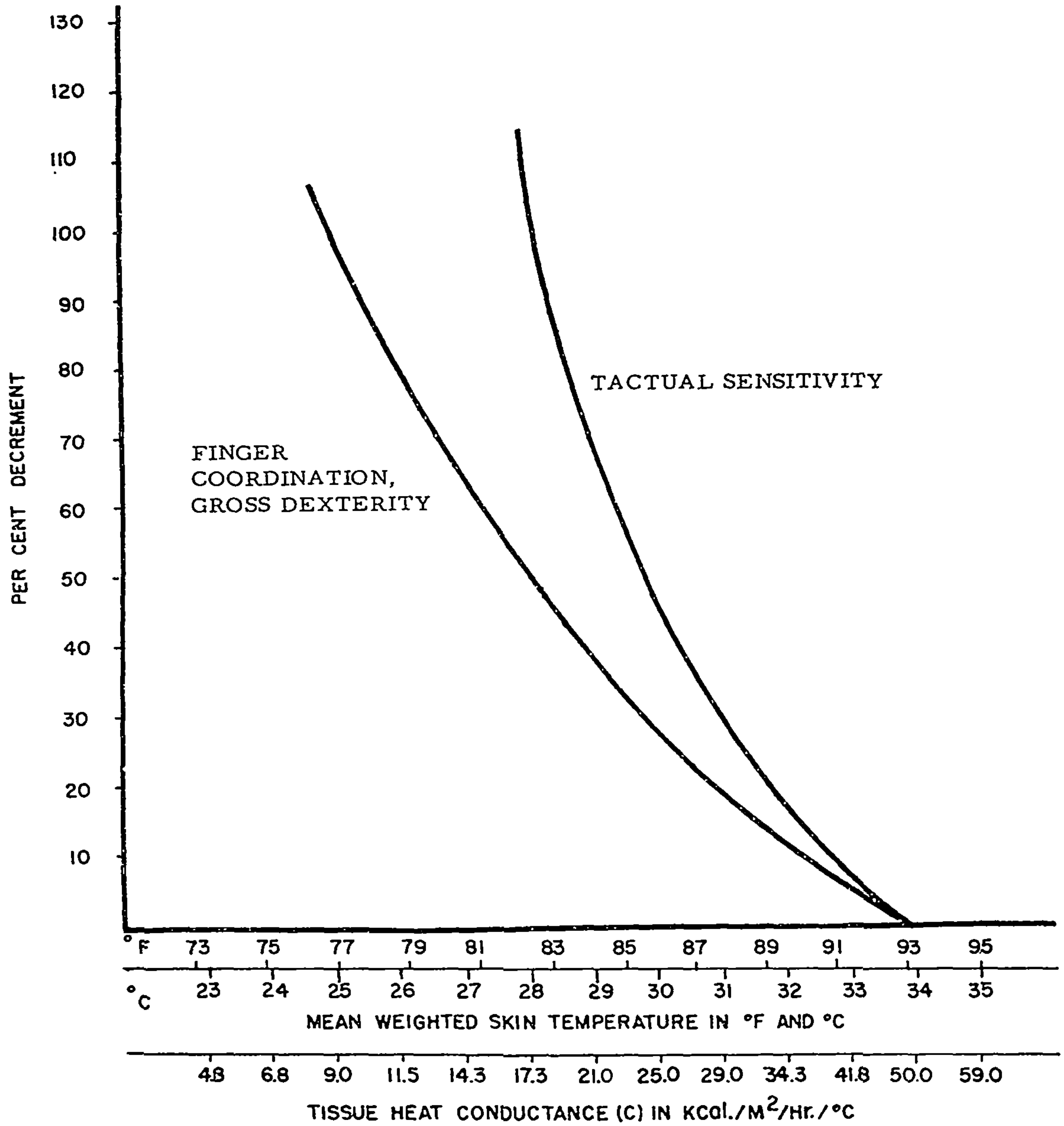

FIGURE IV-2. RELATIVE LOSS IN PERFORMANCE TO BE APPLIED TO TASKS CARRIED OUT IN THE COLD WHERE TACTUAL SENSITIVITY IS CRITICAL OR WHERE GROSS MANUAL DEXTERITY IS INVOLVED.

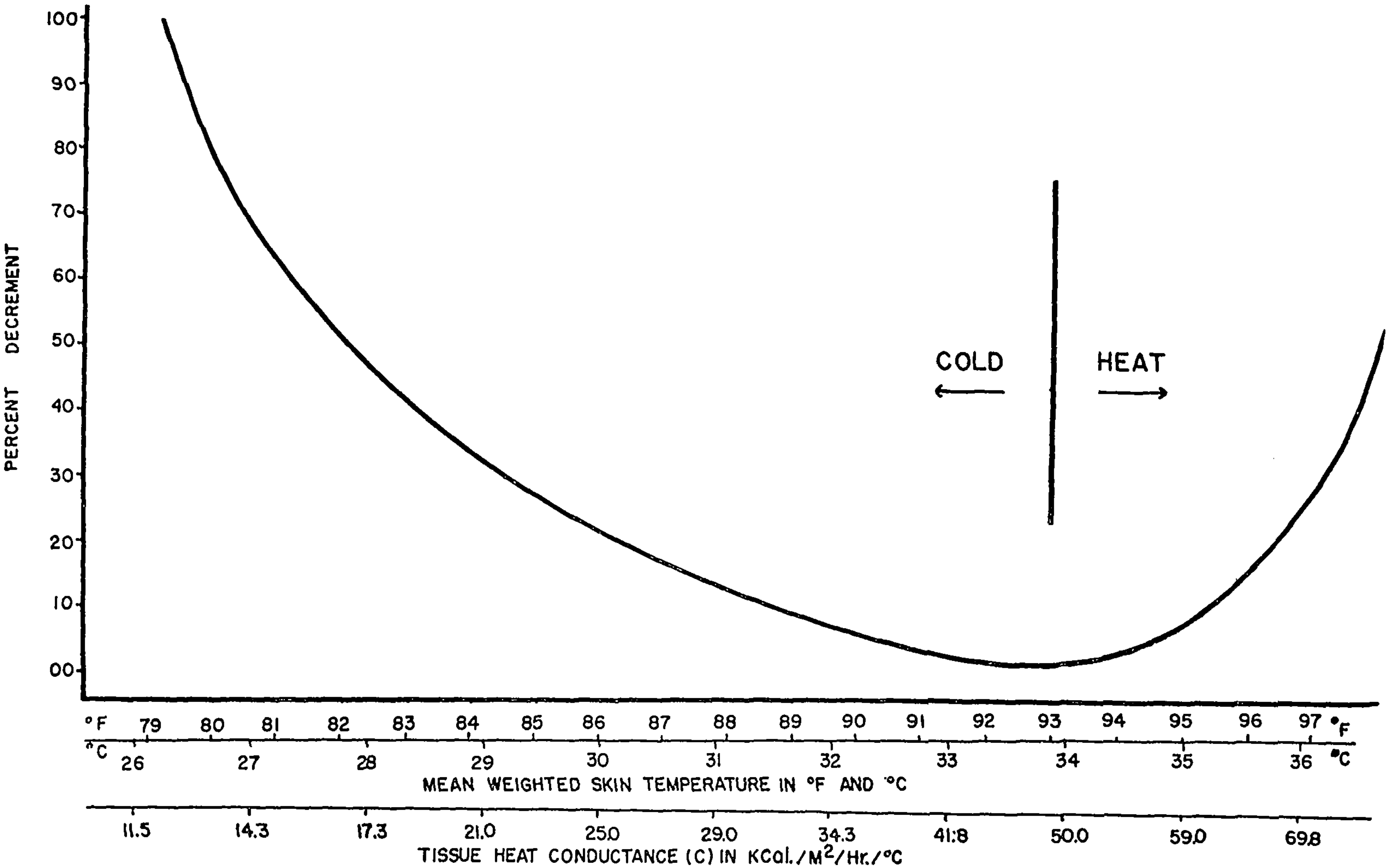

FIGURE IV-3. ATTENTIONAL LOSS FACTOR AS A FUNCTION OF SKIN TEMPERATURE AND RELATED TISSUE HEAT CONDUCTANCE.

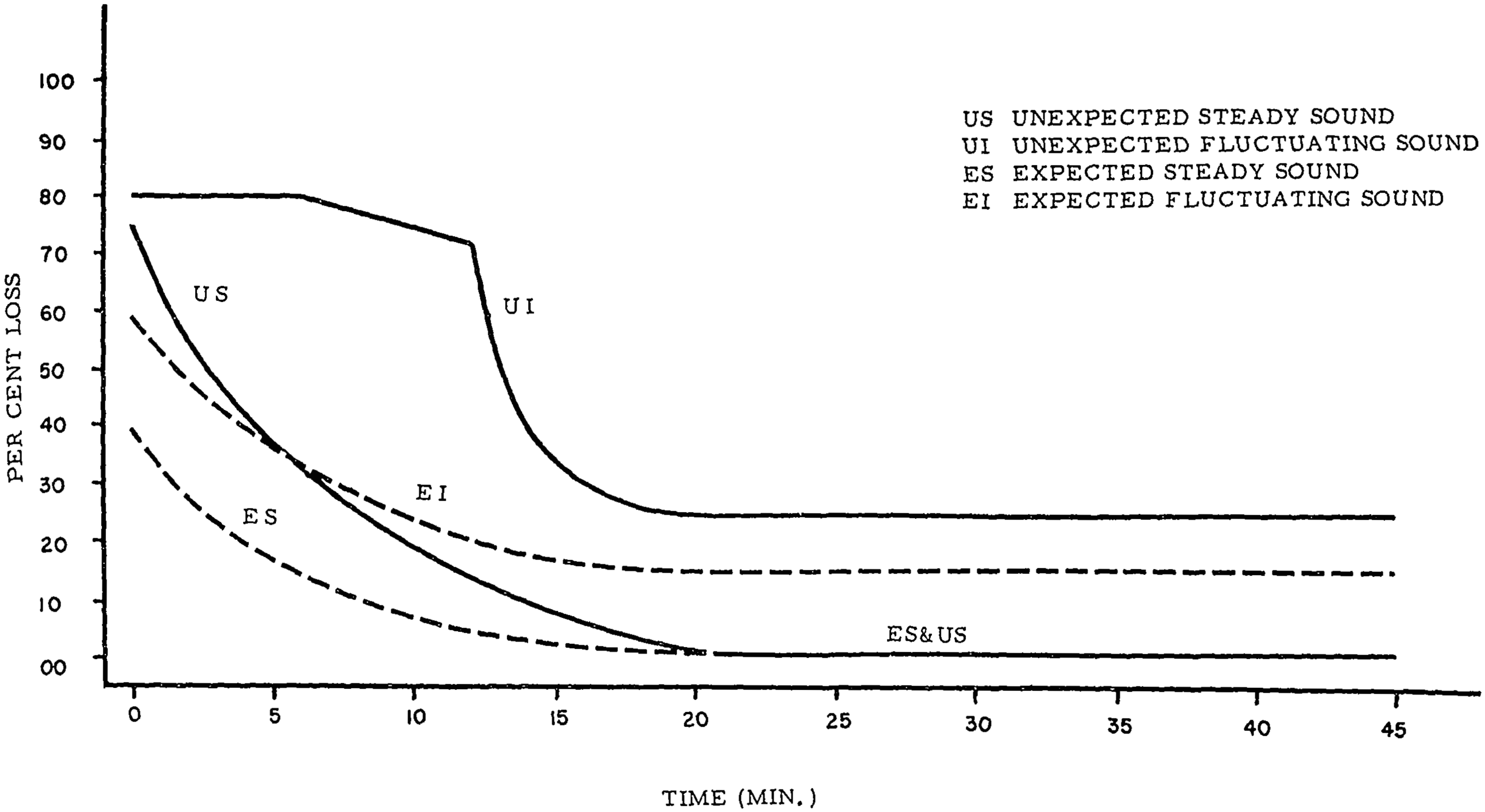

FIGURE IV-4. HYPOTHESIZED ATTENTIONAL LOSS AND RECOVERY OF HABITUATION ASSOCIATED WITH IRRELEVANT SOUND. SOUND IS INITIATED AT t = 0.

V. Appendix

A. Formulae Used in Interpolating in Figure 8

$P(D)_i$ = Initial P(D) at time = 0

$P(D)$ = The difference between the $P(D)_i$ value of interest and $P(D)_i$ for the next lowest curve drawn.

$P(D)_X$ = The final P(D) value where X = 30, 60, 90, or 120 min.

For $P(D)_i$ between .75 ↔ 1.00

$$30 \text{ Min: } X = \frac{P(D)_\Delta\ (.165)}{.250} \; ; \qquad P(D)_{30} = \begin{array}{r} .455 \\ +\ .\ X \\ \hline \end{array}$$

$$60 \text{ Min: } X = \frac{P(D)_\Delta\ (.115)}{.250} \; ; \qquad P(D)_{60} = \begin{array}{r} .350 \\ +\ .\ X \\ \hline \end{array}$$

$$90 \text{ Min: } X = \frac{P(D)_\Delta\ (.080)}{.250} \; ; \qquad P(D)_{90} = \begin{array}{r} .300 \\ +\ .\ X \\ \hline \end{array}$$

$$120 \text{ Min: } X = \frac{P(D)_\Delta\ (.055)}{.250} \; ; \qquad P(D)_{120} = \begin{array}{r} .280 \\ +\ .\ X \\ \hline \end{array}$$

For $P(D)_i$ from .50 ↔ .75

$$30 \text{ Min: } X = \frac{P(D)_\Delta\ (.135)}{.250} \; ; \qquad P(D)_{30} = \begin{array}{r} .320 \\ +\ .\ X \\ \hline \end{array}$$

$$60 \text{ Min: } X = \frac{P(D)_\Delta\ (.115)}{.250} \; ; \qquad P(D)_{60} = \begin{array}{r} .235 \\ +\ .\ X \\ \hline \end{array}$$

$$90 \text{ Min: } X = \frac{P(D)_\Delta\ (.100)}{.250} \; ; \qquad P(D)_{90} = \begin{array}{r} .200 \\ +\ .\ X \\ \hline \end{array}$$

$$120 \text{ Min: } X = \frac{P(D)_\Delta\ (.090)}{.250} \; ; \qquad P(D)_{120} = \begin{array}{r} .190 \\ +\ .\ X \\ \hline \end{array}$$

For $P(D)_i$ from $.25 \leftrightarrow .50$

30 Min: $X = \dfrac{P(D)_{\Delta}\ (.135)}{.250}$; $P(D)_{30} = + \begin{array}{r} .185 \\ \underline{.\ X} \end{array}$

60 Min: $X = \dfrac{P(D)_{\Delta}\ (.075)}{.250}$; $P(D)_{60} = + \begin{array}{r} .160 \\ \underline{.\ X} \end{array}$

90 Min: $X = \dfrac{P(D)_{\Delta}\ (.050)}{.250}$; $P(D)_{90} = + \begin{array}{r} .150 \\ \underline{.\ X} \end{array}$

120 Min: $X = \dfrac{P(D)_{\Delta}\ (.045)}{.250}$; $P(D)_{120} = + \begin{array}{r} .145 \\ \underline{.\ X} \end{array}$

For $P(D)_i$ from $0 \leftrightarrow .25$

30 Min: $X = \dfrac{P(D)_i\ (.185)}{.250}$; $P(D)' = + \begin{array}{r} .000 \\ \underline{.\ X} \end{array} = .X$

60 Min: $X = \dfrac{P(D)_i\ (.160)}{.250}$; $P(D)' = .X$

90 Min: $X = \dfrac{P(D)_i\ (.150)}{.250}$; $P(D)' = .X$

120 Min: $X = \dfrac{P(D)_i\ (.145)}{.250}$; $P(D)' = .X$

B. Equations Found in the Text

		Page
Eq. 1	$P(D_S) = 1 - (1-P_1)(1-P_2) \ldots (1-P_n)$	47
Eq. 2	$P(D) = P(D_S D_A) = P(D_S)P(D_A/D_S)$	52
Eq. 3	$P(D)=P(D_S) \left[P(D_A/D_S) - P(D_A/D_S)(\Delta \%B) \right]$	52
Eq. 4	$(\%C) = 100P(D_S D_A C) = 100P(D_S)P(D_A/D_S)P(C/D_A)$	56
Eq. 5	$(\%C)=100P(D_S) \left[P(C/D_A/D_S)-P(C/D_A/D_S)(\Delta \%B) \right]$	56
Eq. 6	$P(D_d)=P(D_S D_A) = P(D_S)P(D_A/D_S)$	57
Eq. 7	$P(D_d) = P(D_S) \left[P(D_A/D_S) - P(D_A/D_S)(\Delta \%B) \right]$	58

C. Physiological and Environmental Equivalences

Physiological Measures		Atmospheric Conditions				Equivalent Altitude	Equivalent +Gx	
% Art. O_2	% COHb	$P(O_2)$ in O_2-N Mix	pBO_2	PCO in air mm Hg	CO ppm	(x1000')	+Gx Air	+Gx 100% O_2 5 psi
98.00		20.98				0	0	1
97.50		20.00	159.2			1		
97.00		19.4				2	1	2
95.75		18.00		.01		4		3
95.00	0	17.25	132.5			5		
94.00							2	
93.80		16.6				6		
93.75								4
92.50		16.00				7		
92.00								5
91.00	4	15.3		.025	25	8	3	
89.50		14.6				9		6
88.25		14.00	109.5			10		
88.00							4	
87.50								7
87.00	8				50			
85.50	10						5	
85.00		12.9		.06	70	12		8
83.00	12				100			
82.75							6	9
81.88		12.0						
81.20	14	11.8				14		
80.00	15						7	
79.50		11.25	89.8			15		10
79.00	16				125			
77.75		10.8		.127		16		
77.00	18				150		8	
75.00	20				170			
74.50							9	
74.24		10.00						
73.40	22	9.8				18		
72.50	22.5				175			
70.00	25				200			
68.75	26	9.00	73.1	.28		20		
64.00	32	8.1	67.2			22		
Ref. 4.5	3	2	4, 5	1	3	5	4, 5	

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